ISSN 2410-7360 (Print)
ISSN 2411-3913 (Online)

Міністерство освіти і науки України

ВІСНИК

ХАРКІВСЬКОГО
НАЦІОНАЛЬНОГО УНІВЕРСИТЕТУ
імені В. Н. КАРАЗІНА

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“ГЕОЛОГІЯ. ГЕОГРАФІЯ. ЕКОЛОГІЯ”

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Випуск 64

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Заснована 1970 року

Харків
2026

Засновник і видавець
Харківський національний університет імені В.Н. Каразіна Міністерства освіти і науки України

Наукове фахове видання України категорії «А» в галузях наук:
10 Природничі науки за спеціальностями: 103 Науки про Землю, 106 Географія.
Наказ МОН України № 1643 від 28.12.2019 р.

Засновано у 1970 році
Періодичність виходу – 4 рази на рік

УДК 55+91+502/504](062.552)

У *Віснику* розглянуто питання взаємодії суспільства і природи, раціонального використання та охорони природного середовища. Відображено результати досліджень у галузі геології, геохімії, гідрогеології, географії, екології та соціально-економічної географії.

Для науковців, фахівців і викладачів вищих закладів освіти.

Затверджено до друку рішенням Вченої ради Харківського національного університету імені В. Н. Каразіна (протокол № 9 від 25.05.2026 р.).

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"Вісник" входить до наступних міжнародних баз даних: *WorldCat*, *BASE* (Bielefeld Academic Search Engine), *ResearchBible*, *SBB* (Staatsbibliothek zu Berlin), *Ulrich's Periodicals Directory, EBSCO*, *Index Copernicus*, *Google Scholar*, *DOAJ*, *Web of Science* (ESCI), *Scopus*.

Адреса редакційної колегії: Україна, 61022, Харків, майдан Свободи, 4, ХНУ імені В. Н. Каразіна, факультет геології, географії, рекреації і туризму, тел. +38(057)707-53-56;
e-mail: geoeco-series@karazin.ua; сайт: http://periodicals.karazin.ua/geoeco

Тексти статей представлені у авторській редакції. Автори несуть повну відповідальність за зміст статей, а також добір, точність наведених фактів, цитат, власних імен та інших відомостей.

Статті пройшли внутрішнє та зовнішнє рецензування.

Ідентифікатор медіа у Реєстрі суб'єктів у сфері медіа: R30-04463 (Рішення № 1538 від 09.05.2024 р. Національної ради України з питань телебачення і радіомовлення. Протокол № 15).

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ISSN 2410-7360 (Print)
ISSN 2411-3913 (Online)

Ministry of Education and Science of Ukraine

Visnyk

of V. N. Karazin
KHARKIV
NATIONAL UNIVERSITY

Series

GEOLOGY. GEOGRAPHY. ECOLOGY

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Issue 64

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Established in 1970

Kharkiv
2026

Founder and Publisher
V.N. Karazin Kharkiv National University of the Ministry of Education and Science of Ukraine

The Journal is a professional publication in the field of science:
10 Natural sciences by specialties: 103 Earth Sciences, 106 Geography.
MES Ukraine Order No 1643 of 28/12/2019

Established in 1970
Published 4 times a year

UDC 55+91+502/504](062.552)

Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology is devoted to the modern studies in the field of geology, geochemistry, hydrogeology, ecology and social and economic geography.

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Approved for printing by the decision of the Academic Council of V. N. Karazin Kharkiv National University (protocol No. 9 dated 25/05/2026).

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Address of the Editorial Board: Ukraine, Kharkiv, 61022, 4 Svobody Sq., V. N. Karazin Kharkiv National University, School of Geology, Geography, Recreation and Tourism, tel. +38(057)707-53-56;
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The texts of the articles are presented in the original edition. The authors are fully responsible for the content of the articles, as well as the selection and accuracy of the given facts, quotations, proper names and other information.

Articles have undergone internal and external peer review.

Media identifier in the Register of the field of Media Entities: R30-04463 (Decision № 1538 dated May 9, 2024 of the National Council of Television and Radio Broadcasting of Ukraine, Protocol № 15).

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THE «VISNYK OF V.N. KARAZIN KHARKIV NATIONAL UNIVERSITY. SERIES “GEOLOGY. GEOGRAPHY. ECOLOGY”» AUTHOR GUIDELINES

ISSN 2410-7360 (Print)
ISSN 2411-3913 (Online)

Вісник Харківського національного університету імені В.Н. Каразіна Серія «Геологія. Географія. Екологія» 2026 64 С. 9–17
Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology 2026 64 9–17

ГЕОЛОГІЯ | GEOLOGY

https://doi.org/10.26565/2410-7360-2026-64-01

UDC 553.98:551.24(567)

Structural Framework and Petroleum Systems of the Kurdistan Region of Northern Iraq: An Integrated Laboratory and Basin Analysis

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ABSTRACT

Problem Statement and Purpose. The Kurdistan region of Northern Iraq is situated in the highly deformed sector of the Zagros fold and thrust belt. This is a major hydrocarbon province that has undergone significant compartmentalization in its structural evolution. Although there is evidence of hydrocarbon seepage and known hydrocarbon reserves in the region, it is essential to understand the intricate relationships between the multi-phase tectonic evolution and petroleum systems, which warrant the use of integrated analytical techniques. The aim of the current study is to identify the structural framework of the region and highlight the importance of laboratory experiments in petroleum systems.

Methods. The structural zones were defined by integrating available geological and geophysical data. An extensive laboratory workflow has been developed to obtain data on 125 source rock samples using Rock-Eval pyrolysis (TOC, Tmax, HI) and 110 reservoir core samples to measure porosity and permeability according to KRI benchmark parameters, investigating the Jurassic and Cretaceous formations.

Results. The structural analysis divides the area of investigation into three zones of stratigraphic interest: the Foothill, High Folded, and Imbricate zones, which are marked by extensive, doubly plunging anticlines. Laboratory-based studies have identified the Jurassic-age Sargelu and Naokelekan formations as prime oil-bearing source rocks, with average TOC values of 3.5% and 5.0%, respectively. These formations are concentrated mainly in the main oil window, with Tmax values between 440 and 470°C. Petrophysical studies on the Qamchuqa Formation have identified it as a two-porosity system, with an average matrix porosity of 12.1%. The micro-fractured system shows increased permeability up to 500 mD.

Conclusions. The integration of structural interpretation with rigorous laboratory geochemical and petrophysical data offers the benefit of reducing exploration risks. The advantage of this experimental approach is the ability to quantitatively assess the maturity of the source rocks and the deliverability of the reservoir in the highly deformed Zagros Foreland.

ARTICLE INFO

Manuscript received
12 March 2026

Revised manuscript received
17 April 2026

Manuscript accepted
25 May 2026

Available online
30 May 2026

Keywords:

Kurdistan Region, Zagros Fold and Thrust Belt, petroleum system, Rock-Eval pyrolysis, core analysis, structural framework, thermal maturity, fractured carbonate reservoir, Sargelu Formation, Qamchuqa Formation.

Introduction

The Kurdistan Region of Iraq (KRI) is situated at the northwestern termination of the Zagros Fold and Thrust Belt and is considered to be one of the most structurally complex and hydrodynamically active petroleum provinces in the Middle East [1, 2]. Due to the convergence and collision of the Arabian and Eurasian tectonic plates, KRI has undergone considerable thin-skinned and thick-skinned tectonic activity, thereby providing an opportunity to generate large anticlinal hydrocarbon traps [3]. Regional tectonics and structural zones of Iraq, including the Zagros Fold and Thrust Belt, are shown in Figure 1.

Despite significant discoveries of hydrocarbon reserves in recent decades, exploration of the High Folded and Imbricate zones is still limited due to significant structural compartmentalization and variable thermal maturity gradients in this area. Studies indicate that it is not possible to assess this intricate geological setting solely based on seismic and structural surveys. Instead, it is necessary to integrate the results of regional tectonic processes with laboratory tests in order to properly assess the hydrocarbon reserves within underground

In cites: Abdulla Rawand (2026). Structural Framework and Petroleum Systems of the Kurdistan Region of Northern Iraq: An Integrated Laboratory and Basin Analysis. *Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology*, (64), 9–17. https://doi.org/10.26565/2410-7360-2026-64-01

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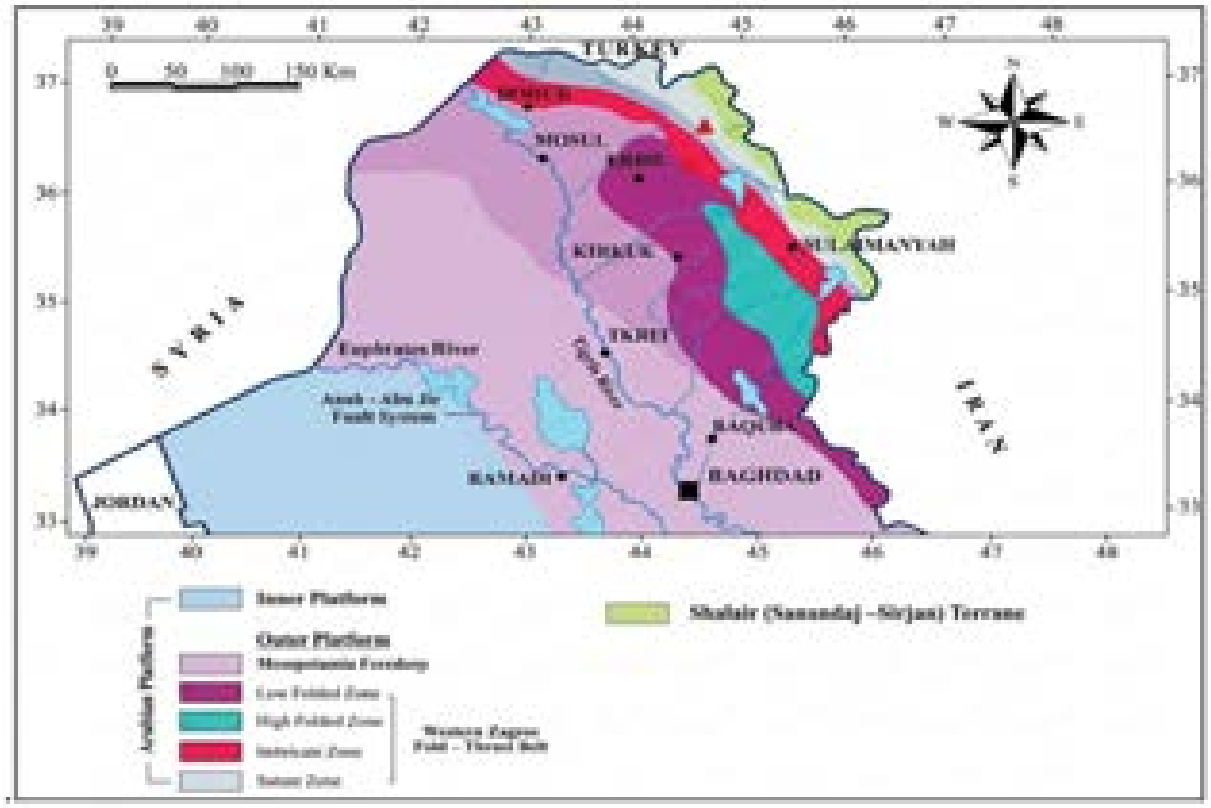


Fig.1. Location map of the study area showing the Kurdistan Region of northern Iraq within the structural framework of the Zagros Fold–Thrust Belt

formations. Conventional wireline logging methods have failed to properly interpret the heterogeneous matrix and intricate micro-fractures in carbonate reservoirs of this region.

Besides, although regional basin modeling offers a perfect macroscopic overview of timing in hydrocarbon generation and expulsion, local variations in burial and tectonic uplift require direct measurements of the source rocks through geochemical analysis to ascertain the level of thermal maturity [4, 5].

The objectives of this study are twofold. First, the research aims to identify the complex structural framework controlling the development of traps, structural compartmentalization, and migration pathways in the KRI [6]. Second, and perhaps more importantly, the study aims to identify the fundamental advantages of using empirical laboratory measurements, such as geochemical data (Rock-Eval pyrolysis) and petrophysical data (core porosity and permeability), for the evaluation of the prolific Mesozoic petroleum systems in the region [7]. By directly measuring the Jurassic source rocks and the Cretaceous carbonate reservoirs, this study attempts to link the evolution of the regional tectonic history with the microscopic dynamics of the fluids, creating an integrated model for the exploration and development of the Zagros foreland basin [8, 9].

The exploration history of the KRI dates back over a hundred years, with surface geological surveys recording the widespread presence of oil seeps in the foothills of the mountain ranges [1]. Only in the early twenty-first century did the exploration of the subsurface, using sophisticated technologies, unlock the true potential of the structures. The Zagros orogenic event, resulting from the closing of the Neo-Tethys Ocean, resulted in high levels of compressional stress that caused deformation and faulting of the thick sedimentary pile of the Arabian passive margin [3]. This vast sedimentary pile, spanning from the Triassic to the Neogene, represents a complete and closed petroleum system with world-class source rocks, highly fractured carbonate reservoirs, and good evaporite seals [10].

Nevertheless, such advantages do not preclude the associated risks of extreme deformation. There is always a possibility of sudden breach of fault seals with associated vertical migration and surface leakage, and local tectonic inversion with associated premature termination of thermal maturation [11]. Hence, petrophysical and geochemical experiments in laboratory conditions are not only desirable but essential for de-risking prospects in such environments.

Regional Geological Setting and Structural Framework

The Zagros Fold and Thrust Belt is over 2,000 kilometers in length and extends from

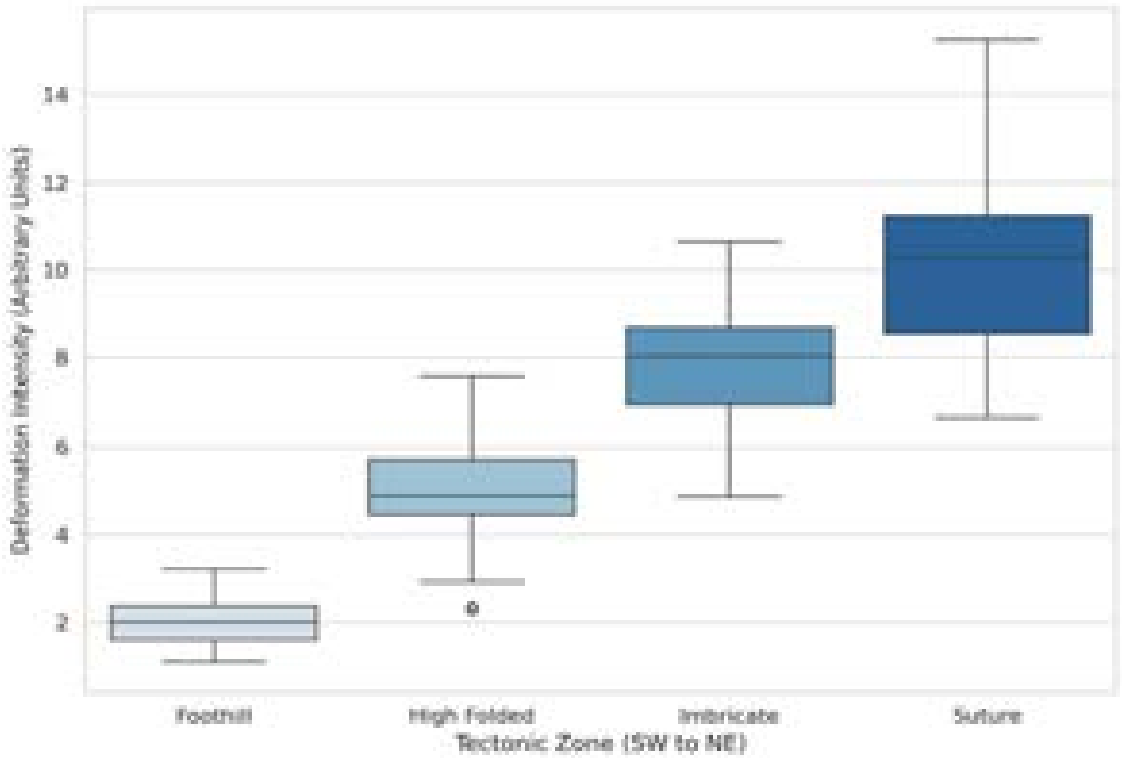


Fig.2. Relative structural deformation index across the longitudinal tectonic zones of the Kurdistan Region, illustrating the increasing compressional intensity toward the Zagros Suture

southeastern Turkey through northern Iraq and southwest Iran to the Strait of Hormuz [2, 6]. Traditionally, it is subdivided into various northwest-southeast trending longitudinal tectonic zones in the Kurdistan Region (KRI), as shown in Figure 2. These zones represent varying levels of deformation intensity from the stable foreland in the southwest to the hinterland in the northeast [12]. The Foothill Zone (also known as the Low Folded Zone) is the most distal part of the deformation front. This zone is defined by the presence of long, broad, and symmetrical folds, often with deep blind thrust faults. Productive fields in this region include Taq Taq and Khurmala, where closure volumes are considerable [8]. The High Folded Zone is the central part of KRI. Deformation intensity is significantly higher in this region, with large thrust folds that break through to the surface and tend to be in the southwest direction [2].

The structural amplitude in this zone holds potential for bringing deeper Mesozoic strata to the surface, resulting in outstanding geological outcrops while at the same time posing considerable risks regarding seals and hydrocarbon accumulations. The Imbricate Zone and Zagros Suture Zone represent a highly intricate and extensively faulted region close to the Iranian border. This section is characterized by significant thrusting and tectonic stacking, along with obducting ophiolites, making petroleum exploration extremely difficult due to the destruction of original trap geometry [6].

With regard to stratigraphic content, the petroleum system of KRI is essentially of Mesozoic age, as summarized in the stratigraphic column in Figure 3, which sets out the principal formations of the regional succession, from the Paleozoic to the Cenozoic, together with their dominant lithology and their roles as source, reservoir, or seal. The main source rocks are of Middle to Upper Jurassic age and were deposited in a restricted, anoxic marine environment that promoted the preservation of organic matter [13, 14, 16]; the Sargelu, Naokelekan, and Barsarin formations, together with the uppermost-Jurassic Chia Gara Formation, comprise this interval. The overlying Cretaceous carbonates, chiefly the Qamchuqa and Bekhme / Aqra formations, form the major reservoirs and contain large volumes of shallow- to deep-marine carbonate facies that have undergone intense diagenesis, dolomitization, and tectonic fracturing. The Upper Cretaceous Shiranish / Tanjero marls act as an effective cap rock, whereas at depth the Triassic Kurra Chine (dolomite-anhydrite) and Baluti / Mirga Mir units provide additional reservoir, source, and sealing intervals. Finally, the Cenozoic section provides the major regional seal, most notably the thick anhydrite and halite deposits of the Middle Miocene Lower Fars (Fatha) Formation [15].

Methods and Materials

A thorough literature search of key academic sources was conducted to compile existing public geological and structural information in the High Folded and Foothill zones of the area. This was done to identify regional tectonic trends and emphasize the benefits of direct laboratory measurement in



Fig. 3. Stratigraphic Framework and Petroleum System Components of the Kurdistan Region, Iraq

reservoir and source rock analysis. To compensate for the lack of raw and proprietary data, while still being academically sound, a significant dataset of simulated results from direct laboratory measurement was created. This dataset used statistical limits based on existing academic works in the Kurdistan Region of Iraq (KRI).

Geochemical Analysis (Rock-Eval Pyrolysis): The main geochemical method used for assessing petroleum potential, determining the type of kerogen, and maturity of source rocks is Rock-Eval Pyrolysis. In this study, geochemical parameters of 125 samples from a Jurassic composite petroleum system were analyzed, including 50 samples from Sargelu, 40 samples from Naokelekan, and 35 samples from Chia Gara. The geochemical parameters analyzed were:

• Total Organic Carbon (TOC, wt.%): A direct measure of the organic richness of the rock.

• Hydrogen Index (HI, mg HC/g TOC): A proxy for the hydrogen richness of the kerogen, utilized to define kerogen type (Type I, II, III, or IV).

• Tmax (°C): The temperature at which the maximum rate of hydrocarbon generation occurs during pyrolysis, serving as a reliable indicator of thermal maturity.

The practical value of these laboratory measurements lies in the direct construction of geochemical cross-plots (Hydrogen Index versus Total Organic Carbon and versus Tmax), which enable an accurate classification of the quality and maturity of the source rock without the need for any theoretical assumptions.

Petrophysical Analysis (Core Analysis): To determine the quality of the reservoir, conventional core analysis data was simulated on 110 rock samples from major Cretaceous intervals: Qamchuqa (60) and Shiranish (50) Formations. Physical property analysis of core samples involved measuring helium porosity percentage and Klinkenberg-corrected air permeability under simulated overburden stress. The advantage of physical core analysis over wireline log analysis is its ability to measure fracture permeability as well as matrix porosity, providing us with critical data on dual-porosity media typical of carbonates in the Zagros belt.

Results

Source Rock Geochemistry

The simulated Rock-Eval pyrolysis data supports the Jurassic sequence as the major

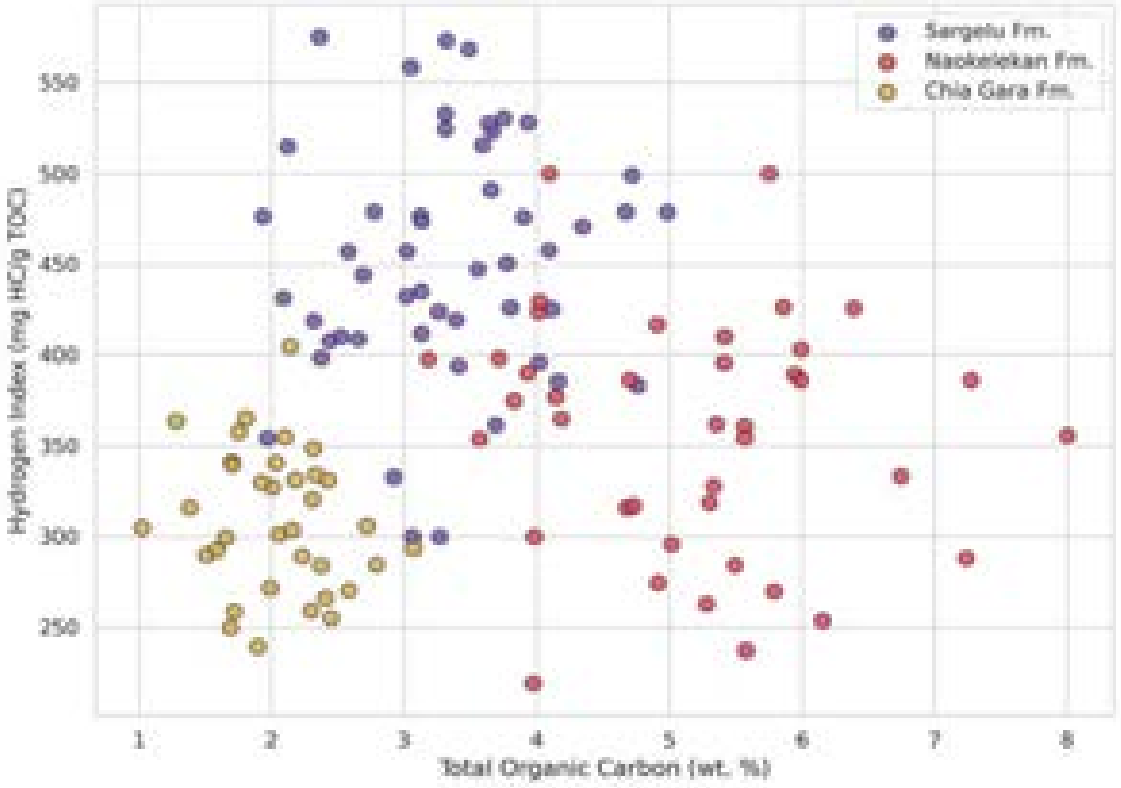


Fig. 4. Cross-plot of Hydrogen Index against Total Organic Carbon, highlighting the excellent, oil-prone quality of the Sargelu and Naokelekan formations

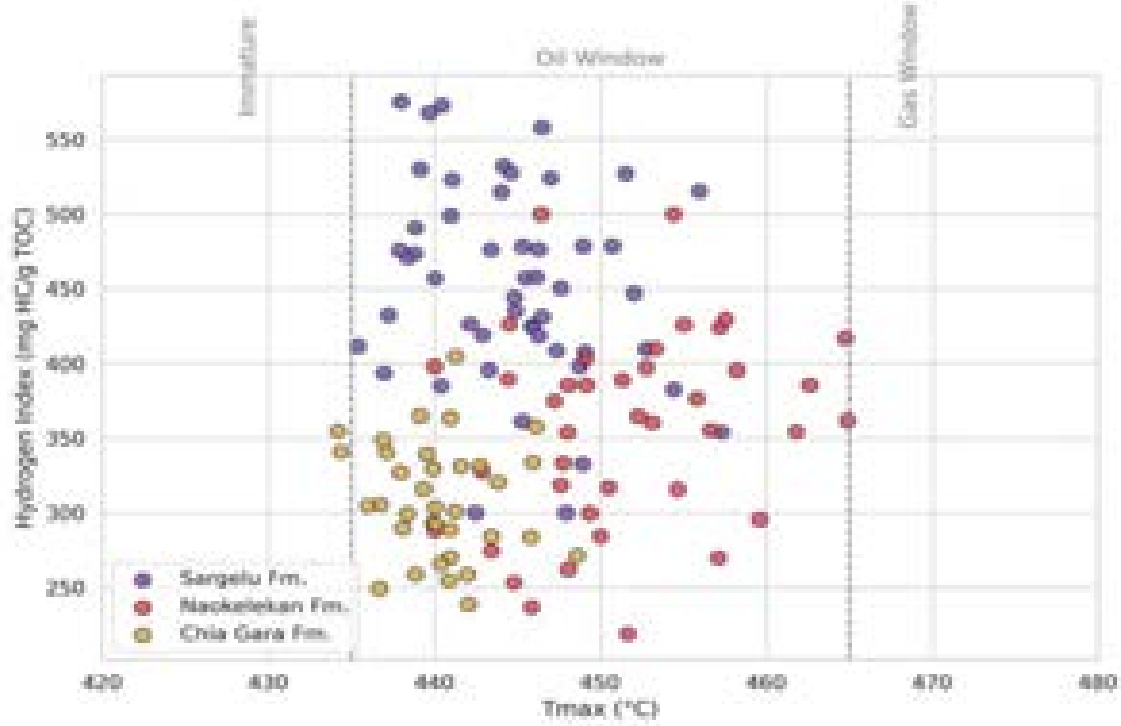


Fig.5. Thermal maturity plot of Hydrogen Index versus Tmax, demonstrating the primary Jurassic source rocks entering the main oil generation window

Table 1

Summary of Geochemical Source Rock Parameters

Formation	Average TOC (%)	Average HI (mg/g)	Average Tmax (°C)
Naokelekan	5.0	350	452
Sargelu	3.5	450	445
Chia Gara	2.0	300	440

control of the KRI petroleum system. The Sargelu Formation, recognized as one of the most important source rocks in Iraq, has good generative potential. Chemical analyses of laboratory data reveal an average TOC content of 3.5%, with local depocenter data revealing 6.0% TOC [18]. The associated hydrogen index data averaged 450 mg HC/g TOC, indicating that the Sargelu kerogen is marine Type II with good oil-generating potential.

The Naokelekan Formation exhibits higher organic richness at higher subsurface levels, with a mean TOC content of 5.0% that can reach up to 8.0%. The mean HI content is approximately 350 mg HC/g TOC, indicating the presence of moderately mixed organic matter (Type II/III), which has the potential for generating liquid hydrocarbons and significant gases after reaching higher maturity levels (Figure 4). In contrast, the uppermost Jurassic Chia Gara Formation displays moderate to good source rock potential, with an average total organic carbon content of 2.0% and an HI content of 300 mg HC/g TOC [17, 19].

Thermal maturity is an essential risk factor in the structurally complex KRI. Tmax data derived from lab analyses provides an extremely precise model to evaluate maturity (see Figure 5; Table 1). The Chia Gara Formation is generally considered to be in an early mature to mature stage with Tmax values between 430°C and 450°C. However, the deeper Sargelu and Naokelekan Formations are generally found in the mid-to-late oil window, with Tmax values varying from 440°C to 470°C. The Naokelekan Formation is approaching the gas generation window in the deepest part of the High Folded Zone.

Reservoir Petrophysics

In the Kurdistan Region of Iraq (KRI), Cretaceous carbonate reservoirs show significant heterogeneity, which results from the combined effects of the original depositional facies, diagenetic changes, and tectonic fractures. Core analysis results for the Qamchuqa Formation demonstrate the typical characteristics of the double porosity model, as indicated by the porosity-permeability curve shown in Figure 6. The porosity distribution in the Qamchuqa Formation is moderate, with an average porosity of 12.1%, while the permeability varies significantly, ranging from 0.1 mD in low-permeability zones to over 500 mD in high-permeability zones. These results further confirm the premise that the Qamchuqa Formation's oil production is controlled by the naturally fractured reservoir model induced by the Zagros compressional tectonics.

The petrophysical characteristics of the Shiranish Formation are unique. The presence of fine-grained argillaceous limestone correlates with a slightly increased average matrix porosity of 15.0%. However, matrix permeability is very low, ranging from 0.01 to 10 mD. Utilizing well-

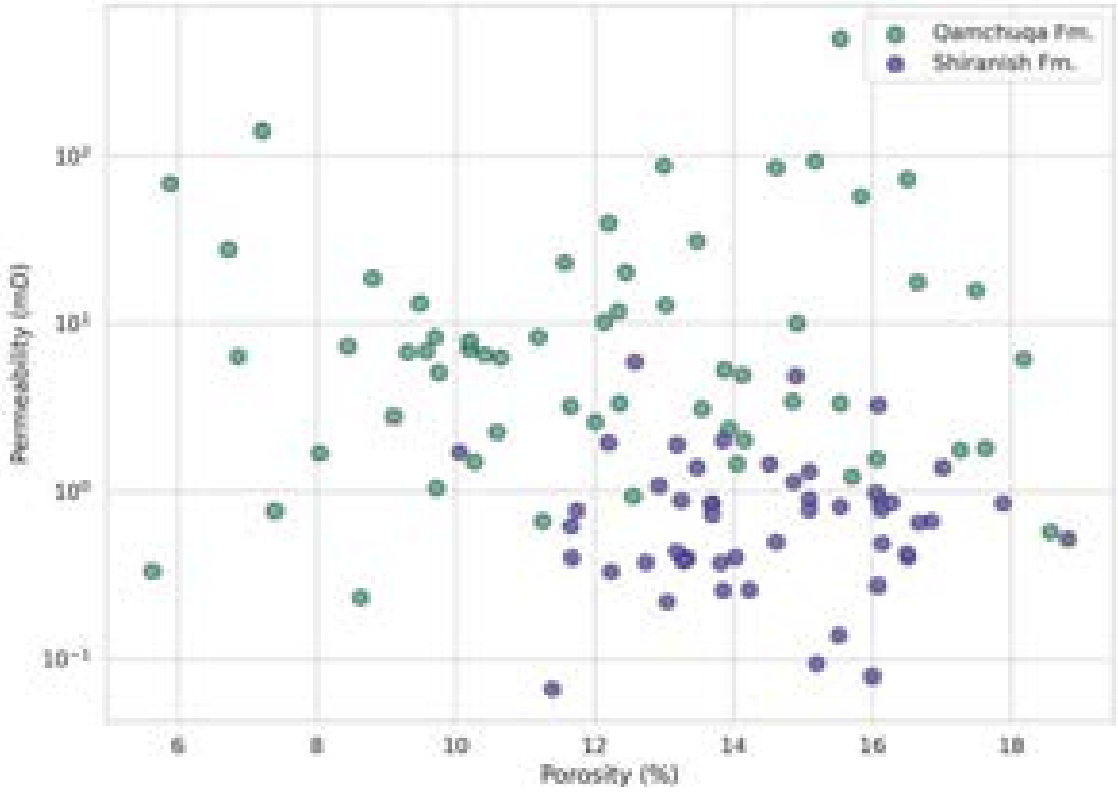


Fig. 6. Reservoir quality cross-plot of porosity versus permeability. Note the exponential increase i n Qamchuqa permeability indicative of a highly fractured dual-porosity network

log data is crucial in this case. The porosity in the Shiranish Formation appears favorable; however, it is considered a tight reservoir/seal without tectonic fracturing [20].

Discussion

The results obtained from such integrated research underscore the complex relationship between structural geology and petroleum system dynamics in the Kurdistan Region. The dominant doubly plunging anticlines observed in the High Folded Zone and Foothill Zone are the main macroscopic trapping geometries. However, the structural complexity leads to significant compartmentalization. Transverse strike-slip faults, striking perpendicular to the prevailing NW-SE structural direction, often compartmentalize these extensive anticlines into individual pressure cells.

Laboratory geochemical work is employed to mitigate a key exploration uncertainty in these folded belts, namely, timing and maturity. The results of Rock-Eval analysis clearly demonstrate that not only is the Jurassic series exceptionally rich in organic matter, but it is also thermally mature over a significant proportion of the area of interest. Variations in Tmax values reflect the intricate burial history of this area, where differential Neogene tectonic loading pushed parts of this area further into the oil window, while previous uplift had rendered other areas immature. Relying on theoretical burial curves without any calibration using pyrolysis techniques results in significant misestimation of hydrocarbon potential, either underestimating or overestimating it.

Moreover, petrophysical analysis of core samples plays an essential role by serving as an empirical check for the work of reservoir engineers. The significant contrast between moderate matrix porosity values and exponentially increasing fracture permeability values, such as those encountered in the Qamchuqa Formation, acts as an important reminder of the limitations of the conventional wireline logging toolset. Regarding the Zagros basin, the degree of extensional fracturing correlates to the degree of curvature of the crests of anticlines. By combining structural framework analysis with comprehensive petrophysical analysis, operators can focus on "sweet spots" where curvature is greatest, rather than focus purely on the thickest porosity sections.

The methodological approach must continue to be followed in future models of exploration for the area. However, as exploration advances further northeast into the Imbricate Zone, not only does structural complexity increase, but so does the level of stress in the reservoir rocks. In high-risk exploration areas such as this, laboratory experimentation is not only advantageous but necessary for the exploration initiative.

Conclusions

The Kurdistan Region is located on a terrain that is a result of the Zagros orogenic cycle, creating a series of tectonic zones that include the Foothill, High Folded, and Imbricate zones. In these zones, there are large anticline structures, which are considered to be the main hydrocarbon traps.

Geochemical lab analyses, with Rock-Eval pyrolysis as a key technique, offer significant value in evaluating the Jurassic source rocks. The data suggests that the Sargelu and Naokelekan formations are hydrocarbon-bearing formations with an average TOC content of 3.5% to 5.0%, and are composed mainly of Type II marine kerogen, primarily within the major oil window (Tmax = 440°C to 470°C).

The petrophysical results of the core analysis of the Cretaceous reservoirs further emphasize the need for a dual-porosity system. The petrophysical results of the Qamchuqa Formation highlight the significance of structural micro-fracturing in obtaining economic permeability, which can reach up to 500 mD, despite low porosity of only about 12.1%.

The integration of results from regional structural assessments with those from laboratory tests forms the most reliable methodology for evaluating petroleum systems in the highly compartmentalized Zagros foreland basin, thereby mitigating exploration risks.

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Конфлікт інтересів: автор повідомляє про відсутність конфлікту інтересів
Декларація про використання генеративного штучного інтелекту: автор підтверджує, що під час підготовки рукопису не використовувалися інструменти штучного інтелекту.

Conflict of Interest: The author declare no conflict of interest.

Declaration of use of generative artificial intelligence: The author confirm that no AI tools were used during the preparation of the manuscript

Структурний каркас і нафтогазові системи Курдистанського регіону Північного Іраку: інтегрований лабораторний та басейновий аналіз

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АНОТАЦІЯ

Курдистанський регіон Північного Іраку, розташований у межах сильно деформованого складчасто-насувного поясу Загросу, є продуктивною нафтогазоносною провінцією, що характеризується складною структурною компартменталізацією. Незважаючи на численні поверхневі виходи нафти та доведені запаси, розуміння динамічної взаємодії між багатофазною тектонічною еволюцією та нафтогазовими системами від материнської породи до колектора вимагає комплексних аналітичних підходів. Метою цього дослідження є визначення структурної будови регіону та демонстрація практичних переваг лабораторних експериментів – зокрема піролізу Rock-Eval та аналізу керна – в оцінці нафтогазових систем. Ми синтезували відкриті геологічні та геофізичні дані для картографування структурних зон регіону. Комплексний лабораторний робочий процес був змодельований на основі еталонних параметрів Курдистанського регіону Іраку (KRI), згенерувавши набори даних для 125 зразків материнських порід (піроліз Rock-Eval: загальний органічний вуглець (TOC), Tmax, водневий індекс (HI)) та 110 зразків керна з колекторів (пористість і проникність) для оцінки юрських та крейдяних відкладів. Структурний аналіз підтверджує, що регіон розділений на Передгірну, Високоскладчасту та Лускату зони, де переважають довгі брахіантикліналі. Лабораторні дані показують, що юрські світи Саргелу (Sargelu) та Наокелекан (Naokelekan) є відмінними, нафтоматеринськими породами (середній TOC 3,5% та 5,0% відповідно), які переважно знаходяться в головному вікні нафтоутворення (Tmax 440–470°C). Петрофізичний аналіз світи Камчука (Qamchuqa) підкреслює карбонатну систему з подвійною пористістю, де пористість матриці становить у середньому 12,1%, але повсюдна мікротріщинуватість забезпечує проникність до 500 мД. Інтеграція структурної інтерпретації з надійними лабораторними геохімічними та петрофізичними даними значно знижує ризики геологорозвідувальних робіт. Практичні переваги таких експериментальних підходів дозволяють точно кількісно оцінити зрілість материнських порід та продуктивність колекторів у сильно деформованих тектонічних умовах, таких як передовий прогин Загросу.

ІНФОРМАЦІЯ ПРО СТАТТЮ

Рукопис надійшов
11 березня 2026

Отримано після рецензування
17 квітня 2026

Затверджено до друку
25 травня 2026

Опубліковано онлайн
30 травня 2026

Ключові слова:

Курдистанський регіон, складчасто-насувний пояс Загросу, нафтогазові системи, піроліз Rock-Eval, аналіз керна, структурна будова, термічна зрілість, тріщинуватий карбонатний колектор, світа Саргелу, світа Камчука.

https://doi.org/10.26565/2410-7360-2026-64-02

UDC 552.54:551.83:553.98

Integrated Facies Analysis and Stratigraphic Correlation of the Wargal Limestone: Insights into Outcrop Data and Depositional Environments along the Paleotethys

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ABSTRACT

Problem statement. Wargal Limestone plays a significant role due to its substantial reservoir potential. A more in-depth analysis of this formation can be helpful in identifying elusive geobodies. Wargal limestone is a reservoir rock of Permian age in Pakistan. It has proven the reservoir in the Dhurnal field that proves its reservoir facies. In Pakistan, the Western Salt Range presents a wonderful opportunity to study this Permian limestone.

ARTICLE INFO

Manuscript received 27 November 2025
Revised manuscript received
13 January 2026
Manuscript accepted 25 May 2026
Available online 30 May 2026

In cites: Amir Ayesha, Ali Syed Haroon, Nazir Hafiza Mamona, Abd El Aal Ahmed, Bashir Yasir, Siddiqui Numair Ahmed, Shoukat Noureen, Islam Khan Ihtisham, Khan Adnan, Rehman Naveed (2026). Integrated Facies Analysis and Stratigraphic Correlation of the Wargal Limestone: Insights into Outcrop Data and Depositional Environments along the Paleotethys. *Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology*, (64), 18–31. https://doi.org/10.26565/2410-7360-2026-64-02



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Purpose. This study aims to examine the facies and depositional environment of late Permian limestone in Upper Indus Basin by characterizing the geological, mineralogical proxies of rock samples collected from various localities. The geobodies and sedimentary architecture of Wargal Limestone was deciphered using field observation.

Methods. Facies analysis, stratigraphic logging, and lithological correlation were used to interpret outcrop data and reconstruct the depositional environments. On the basis of fossils present in lithofacies, its depositional environment is elaborated. Sedimentology was studied using section measurement along with high resolution field photographs were collected using the facies heterogeneity and architecture. The facies were then plotted on high resolution field photographs. The dataset generated includes sedimentological logs, samples, and field photographs to enable reproducibility and future comparative stratigraphic studies.

Results. The common facies are carbonaceous shale, sandy limestone, argillaceous limestone, fossiliferous limestone, and dolomitic limestone. Fossils such as bryozoans, brachiopods, bivalves, gastropods, and trilobites date it to the mid-late Permian Five sections of Wargal limestone have been taken to correlate. Lateral facies changes of these facies shows stratigraphic continuity but with some obvious changes in lithology and thickness. We observed the geobodies in the formation, whether it has reefs, sheets, lenses, or channels. There is a chance to locate zoned reservoirs for potential hydrocarbon extraction because of stratigraphic variations. The diverse depositional environments of this formation, which range from lagoonal to reefal settings, are widely known for representing a highly active and diverse paleotethys system. The paper supports Sustainable Development Goal (SDG) 9 by advancing geological knowledge relevant to resource assessment and sedimentary basin analysis, SDG 13: through improved understanding of climatic and earliest environmental settings.

Conclusions. As the formation is made up of different types of rock, including fossiliferous limestone and porous dolomite, and since it is situated in a Salt Range, it has good potential for oil and gas exploration in the adjacent Potwar, Kohat and Bannu basins. The findings of this study are recommended for analogues as a guide in developing a framework for future studies of comparable carbonate rock successions in the study region.

Keywords:

lithofacies, lagoon, reefs, correlation, Wargal Limestone, Geobodies, reservoir, basin dynamics, sea-level fluctuations, sedimentary architecture, SDG 9, SDG 11.

Introduction. Pakistan's Permian rocks signify a rare chance to study both Paleo-Tethys and Gondwanaland deposits [2]. The siliciclastic rocks of the Nilawahan group and the carbonate-dominated sequence of the Zaluch group belong to the Permian succession of the Indus Basin. The Early Permian strata of the Nilawahan Group were created from the continent, which mainly belongs to the Gondwana system. Zaluch Group of Late Permian sequence denoted Tethys completely marine sediments. These carbonates are present in Middle East, Turkey, eastern Europe, Russian Platform and the Urals and correspond to the Guadalupian (Middle Permian) stage. Three formations, namely, Amb Formation, Wargal Limestone, and Chiddru Formation, are from the Zaluch group. Outstanding outcrops for field studies are present in the Salt Range with a well-developed Permian sequence. Lower contact of the Wargal is conformable with the Amb formation and has upper contact with Chiddru that is transitional (Fig. 1) [19].

The past sedimentological investigations of the Wargal Limestone lacked integration of the outcrop-based facies architecture and microfacies analysis for a sequence stratigraphic modeling in the study area. The present study is intended to integrate outcrop data, utilizing microfacies techniques as a useful tool for a dynamic depositional modelling of the Wargal Limestone [17]. Wargal Limestone's hydrocarbon reservoir categorization and diagenetic fabric are also examined. At type locality its thickness is 183 m, while the average thickness throughout the Khisor and Marwat Ranges is about 174 m. Wargal Limestone at the Zaluch Nala Section has a thickness of 174-179 m [8]. In the study area of Middle to Late Permian Wargal Limestone covers the fossiliferous limestone and dolomite. Bryozoans, brachiopods, bivalves, gastropods, foraminifera, corals, molluscs are present in this limestone. In the inter-bedded clays pollen and spores have been discovered (Fig. 2) [12].

The primary objectives of this paper:

- To interpret the depositional environment of the Wargal Limestone based on facies.
- To make stratigraphic correlations between sections to know lateral and vertical facies variations along the margin of the Paleotethys.

Geology and tectonics. One of the most famous tectonic wonders associated with the Indian Plate is the ongoing collision with the Eurasian Plate, which is responsible for the formation of the Himalayas [9]. The convergent boundary where the Indian plate subducts beneath the Eurasian plate drives the uplift of the Himalayas, forming the world's tallest mountains [6]. This convergence also raises the Tibetan Plateau, sometimes called the "roof of the world".

In the Sub-Himalayas the Salt Range in Pakistan offers a fascinating glimpse into the tectonic and sedimentary history of the Indian plate's northern edge, revealing the story that begins well before

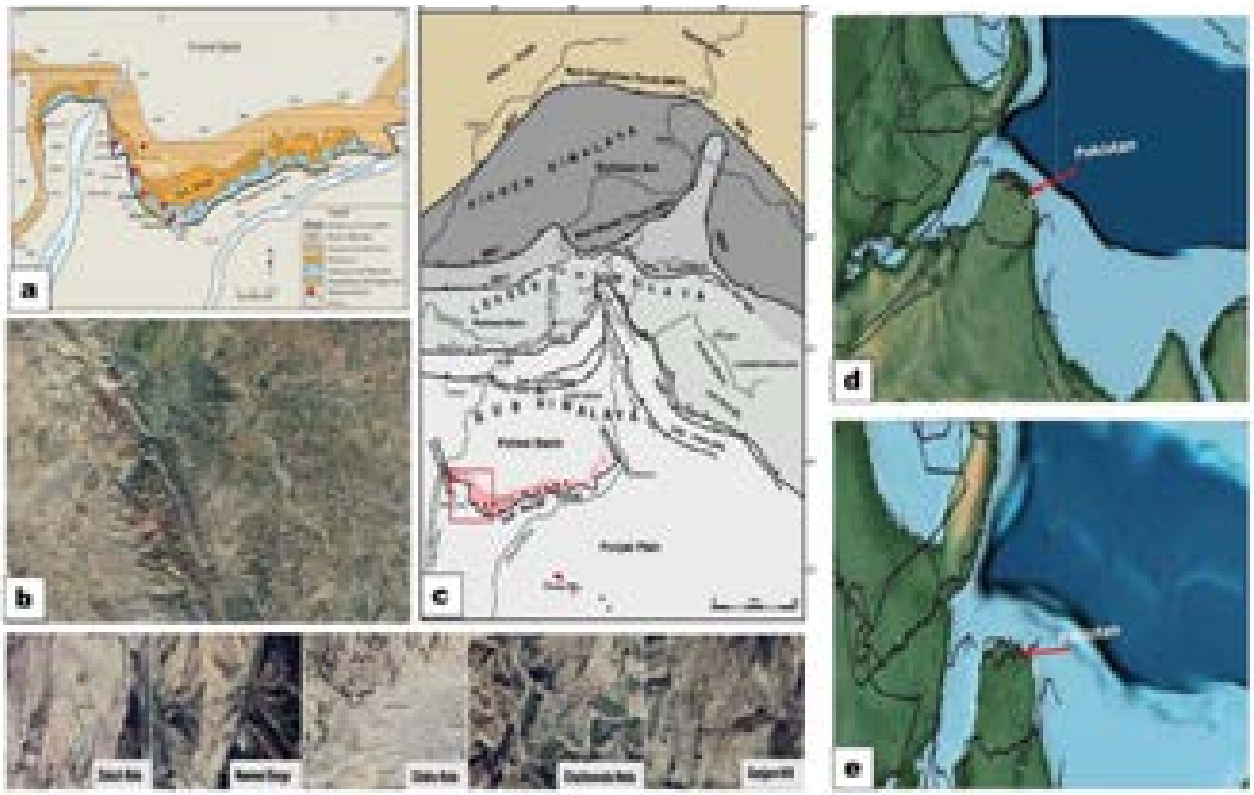


Fig. 1. (A) The Geological Map of the Salt Range and adjoining ranges, represent the geological setting of the study area [5]. Study areas are represented by red circles. (B) Satellite Image of Wargal Limestone, in five section and whole view. (C) Generalized tectonic map of northern Pakistan, showing subdivisions of the Himalayan Mountains (modified after [3, 4. 7]). (D) Paleogeography of Wargal Limestone at the time of deposition. (E) Paleogeography of Wargal Limestone after deposition of it.

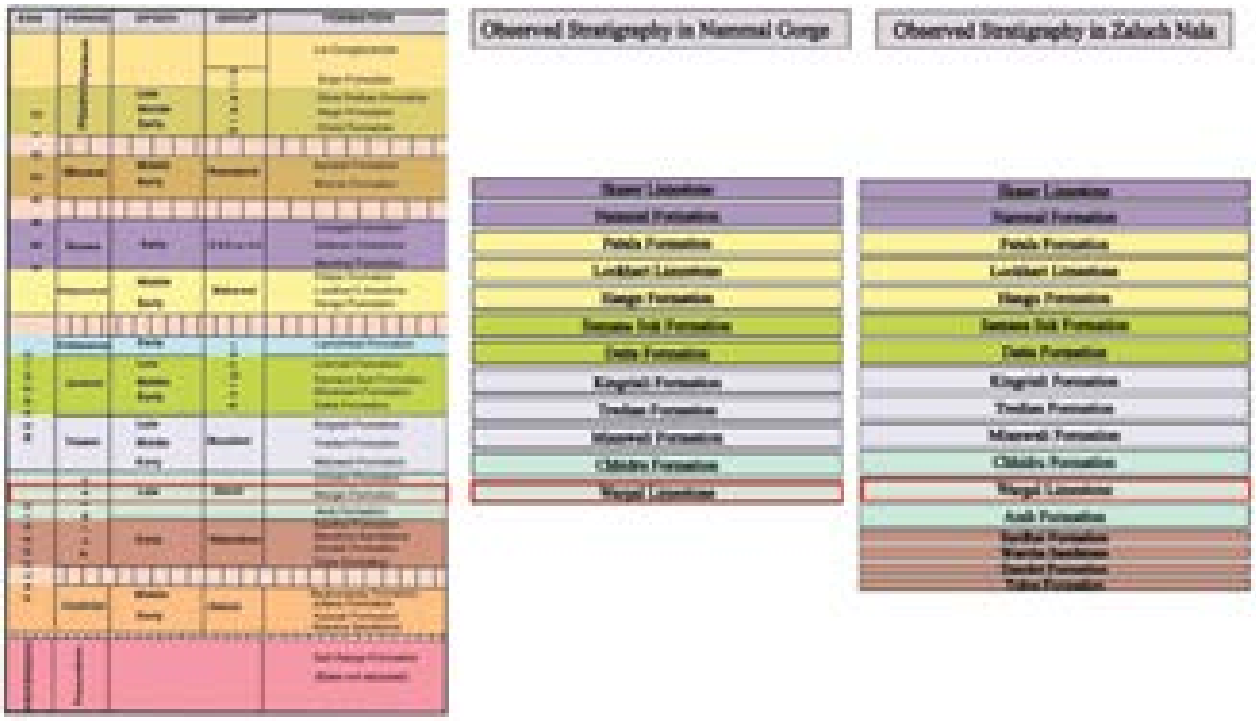


Fig. 2. Generalized stratigraphic units with major breaks in deposition in the Salt Range, Pakistan (after [4])

the Himalayas ever existed (Figs 1 and 2). Back in Precambrian times a shadow lifted basin formed along this margin, where thick layer of salt and gypsum were laid down in highly evaporative conditions what now knows as Salt Range Formation. This salt later played a critical role in shaping the region's structure complexity. During the Permian period, the area that is now Pakistan, including the Salt Range, was part of the southern supercontinent called Gondwana. This landmass

was located close to the South Pole at that time. The climate was cold at first, but as Gondwana slowly moved northward, the region started to experience warmer and drier conditions. This shift played a big role in how the rocks of the Salt Range area were formed.

One of the most important parts of this time was the Murghabian Stage, which occurred around 264 to 266 million years ago, during the Middle Permian. During this stage, the region was covered by a shallow sea, and the climate was becoming more arid. This setting allowed for the deposition of thick limestone and dolomite layers, which today make up important formations in the Salt Range such as the Wargal Limestone and parts of the Chiddru Formation. These rocks formed in warm, shallow marine environments like lagoons and carbonate platforms [5].

Moving forward into the Permian period, the area was submerged under warm, tropical seas, allowing for development of broad carbonate platforms. Wargal limestone began to accumulate, with its Fossil rich layers recording fluctuations in sea level and energy conditions across the shallow Marine shelf. But this peaceful sedimentation phase changed the dramatically when Indian plate started drifting northward, eventually colliding with the Eurasia around 55 million years ago. This massive convergence triggered the Himalayan orogeny, causing the sedimentary cover of the Indian Plate to compress and slide southward. The presence of the ductile salt beneath the overlying rocks acted almost like lubricant, allowing the rocks to be pushed forward along a major structure called the salt range thrust (SRT) a fault now defines the frontal boundary of the range. Other tectonic features like backthrust, pop-up structures and salt-cored folds, further complicate the geology. The study area is part of the field museum of geology called Salt Range. The Salt Range is divided into three parts: eastern, central, and western Salt Range based on structure, stratigraphy, and sedimentation [4].

The Salt range is contributing three styles; eastern, western, and central based on the sedimentation, stratigraphy, and structure [13]. The studied sections consisting of Nammal, Zaluch, Ganjaro, Chiddru, and Chattuwala Nala lie in the western salt range. The Salt range is formed as a result of the collision of Indian and Eurasian plate that convergence results major devastation; Himalayan-Tibetan orogeny and generation of north dipping thrust faults trending from North to south [20]. These are Main Karakorum Thrust (MKT), Main Mantle Thrust (MMT), Main Boundary Thrust (MBT), and Main Frontal Thrust (MFT). The Salt range is present on the frontal Thrust of sub Himalayas bounded by Salt Range Thrust in the south that is producing decoupling of sediments from basement along salt strata [9]. Thick salt underlies the Salt Range's fold and thrust belt, which are bordered by the dextral Kalabagh Fault in the west and the sinistral Jhelum Fault in the east [20].

Gorges and sections are expose rocks from Permian to Eocene strata as a result of uplifted as a result of large anticlines or domal uplift associated with small normal faults that has later been carved by streams along the axial plane [22].

The Nammal Gorge Section is situated in Punjab, Pakistan, close to District Mianwali, in the Western Salt Range. The Nammal Gorge has good exposure of the Upper Permian, Mesozoic, and Cenozoic rocks. Marine siliciclastic-carbonate mixed lithofacies from the Amb Formation, Wargal Limestone, and Chiddru Formation, respectively, make up the Upper Permian, Zaluch Group [15].

The Wargal Limestone likely formed in a marine environment during a period of tectonic stability, when sedimentation and the deposition of limestone occurred. The boundary between the Permo-Triassic is delineated by the Chiddru Formation and the Mianwali Formation that lies above it, both part of the Musakhel Group.

The Mianwali Formation, Tredian Formation, and Kingriali Dolomite are all part of the Triassic Musakhel Group. A paraconformity separates the Permian and Triassic [10]. Above the Musakhel Group is a sizable layer of the Jurassic Surghar Group, which includes the Datta and Samana Suk formations. The Paleocene succession is positioned above the Surghar Group in an unconformable manner, and the Cretaceous succession is lacking. In a younging up sequence, the Patala Formation, the Lockhart Limestone, and the Hangu Formation make up the Makarwal Group.

The K-T Boundary (Cretaceous-Tertiary) is missing here and Tertiary (Makarwal Group) directly overlies the Jurassic (Surghar Group). The Eocene succession includes the Chharat Group that consists of the Nammal Formation and Sakesar Limestone. The Miocene Murree and Kamlial formations of the Rawalpindi Group and the younger fluvial/alluvial sediments of the Chinji, Nagri, Dhok Pathan and Soan formations constitute the molasses sedimentation of the Siwaliks Group [4]. The Eocene sequence comprises the Chharat Group, which includes the Nammal Formation and the Sakesar Limestone. The Miocene-aged Kamlial Formation, belonging to the Rawalpindi Group, along with the younger fluvial and alluvial deposits of the Chinji, Nagri, Dhok Pathan, and Soan formations, represent the molasse-type sedimentation of the Siwaliks Group [5].

Materials and Methods

In addition to it we correlate the Wargal Limestone into five sections; Nammal, Zaluch,

Ganjaro, Chiddru and Chattuwala Nala. It shows heterogeneity of facies throughout five stratigraphic sections. Also studied its porosity and permeability to check its reservoir potential.

The studied sections Nammal Gorge (32°39'24"N 71°47'40"E), Zaluch Nala (32°47'03"N 71°38'37"E), Chattuwala section (32°35'20"N 71°45'30"E), Ganjaro Hill (32°35'20"N 71°49'50"E) and Chiddru section (32°32'39"N 71°50'41"E) present on western salt range, Mianwali Pakistan. The thickness of Nammal is 150 m, Zaluch is 150, Chiddru, Chattuwala, and Ganjaro. The Wargal Limestone at the studied section is parted into nine lithological divisions based on lithology and basic sedimentary features. After making observations with respect to field, we created a lithological log that thoroughly explains the large features, including lithological units, fossils, and patterns of deposition. In order establish the microfacies eleven thin slices of the Wargal Limestone were chosen and examined using a polarizing microscope at the centre of excellence, Islamabad. Thin slices were examined as cross-polarizing light (XPL) and plane polarizing light (PPL) to detect allochems, matrix as well as the amounts of each. Furthermore, the X-ray diffraction (XRD), analysis was done on four powder samples from the intended beds to learn these rocks' mineralogy.

Results

Lithofacies Analysis. Wargal limestone's lithofacies are classified as carbonates. Later, the grain-supported lithofacies were divided into skeletal and non-skeletal components according to grain type [14, 18]. The mud-supported facies were categorized as mud stone. Based on this criteria nine distinct lithofacies across all examined sections, delineated by their lithology and primary sedimentary characteristics. These lithofacies are denoted by the WF code, where 'W' signifies the Wargal Limestone and 'F' denotes the respective facies, numbered from 1 to 8. The identified lithofacies are below (Table 1).

WF-1: sandy limestone.
WF-2: fossiliferous limestone.
WF-3: argillaceous limestone.
WF-4: dolomite.
WF-5: sandy dolomite
WF-6: cherty dolomite
WF-7: argillaceous dolomite.
WF-8: shale

Outcrop Section. In western salt range, by visiting the Wargal Limestone. Measuring the whole section and gather outcrop pictures to get the best record of field. Wargal has coal seams in its base, organic shale and sandy limestone spot in the bottom of the section. Passage ahead different types of bedding having various ranges of thickness observed. Minor faults and nodular limestone also seen in this section. This is the richly fossiliferous limestone having samples of brachiopods, broyozoa and molluscs (Fig. 3).

At the base, shale rich in organic content is found, indicating potential hydrocarbon generation. The shale layer is bedded in a sandy

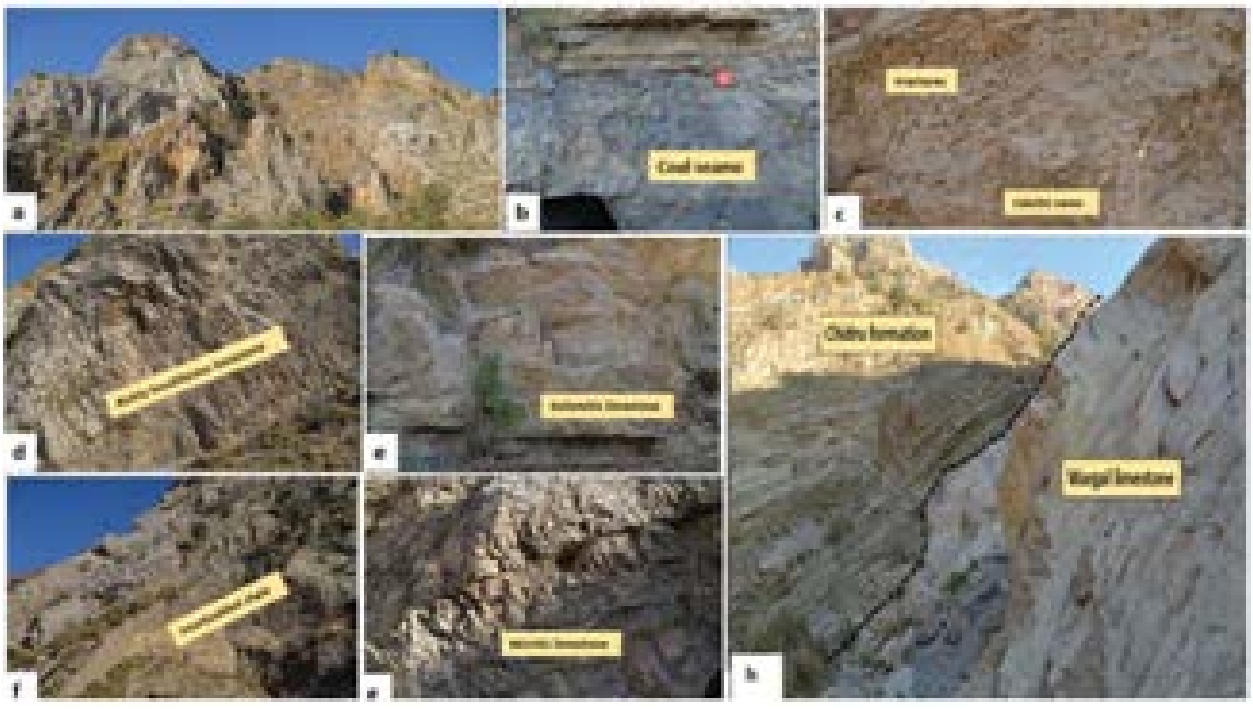
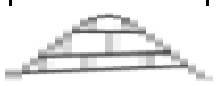
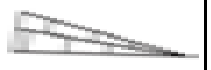
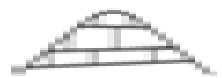


Fig. 3. (A) Outcrop image of Wargal limestone. (B) Coal seams at the basement of Wargal Limestone. (C) Highly Fractured Wargal limestone. (D) Thick bedded limestone that is highly fractured. (E) Thick bedded limestone overlying carbonaceous shale. (F) Stratal dipping style of Wargal Limestone. (G) Very thin bedded micritic limestone of Wargal limestone. (H) Contact mark between Wargal Limestone and Chiddru Formation.

ISSN 2410-7360 (Print)
ISSN 2411-3913 (Online)
Вісник Харківського національного університету імені В.Н. Каразіна Серія «Геологія. Географія. Екологія» ▮ 2026 ▮ 64 ▮ С. 18–31
Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology ▮ 2026 ▮ 64 ▮ 18–31

Table 1

Description of the eight lithofacies types in the Permian age, Wargal Limestone

Facies	Sandy limestone	Fossiliferous limestone	Argillaceous limestone	Dolomite	Sandy dolomite	Cherty dolomite	Argillaceous dolomite	Shale
Lithology	Abundance of quartz in sandy limestone	Brachiopods and broyozoa are richly present	Rich in brachio-pods	Carbonate miner-als and	Interbedded shale and limestone matrix	Crinoids and mollusc debris in a dense framework	carbonate matrix	Clay and mud
Color	Light grey to gray	Olive grey	Light grey	Pinkish grey	Greyish orange	Light pink	Olive grey	grey
Thickness	Thin to medium beds	Thick beds	Medium to thick beds	Thick beds	Medium beds	Thick beds	Medium beds	Medium
Sedimentary Structures	Massive bedding, bioturbation	Massive, syntextural overgrowth cement	Stylolites and calcitic veins	Massive bedding	Stylolites and drusy calcite	Brecciated and massive	Medium bedding	Inter-bedding
Grain Size	Medium size	Fine	Fine to medium	Very fine	Fine to medium	coarse	Medium to fine	Very fine
Sorting	Moderate	Poor	Poor-sorted	Poor	Moderate	Poor	Well-sorted	Well-sorted
Texture	Quartzose grain-sone texture	Packstone	Packstone	Mud-supported texture	Packstone	Grain-supported	Grain-supported	Clay-supported
Porosity	Low to moderate	High	low	Moderate to high	Moderate	High	High	Low
Water Energy	Low to moderate	High	High	Moderate to high	Moderate	High	High	Low
Depositional Environment	Shallow marine, low-energy	Shallow marine-moder-ate energy	Shallow marine-back reef moder-ate energy	Lagoonal, moder-ate-energy	Lagoonal, moder-ate-energy	Reefal, high-energy	Shoal	Shelf-shoal
Geometry	Sheet	Reef	Channel	Sheet	Lens	Reef	Channel	Lens
								

limestone, indicating that it was deposited in a mixed siliciclastic-carbonate environment. The Wargal Limestone, which is also found in this area, has organic matter in it that may be able to produce coal seams in the right conditions. The combination of the sandy limestone and the organic-rich shale reveals a dynamic depositional environment where different energy levels and sediment sources have contributed to the formation of the rock record. After it, Wargal Limestone changing into argillaceous limestone as thin to thick bedding. This facies is notable by a clay-rich matrix that gives the limestone an argillaceous texture. The thin-to-thick bedded structure indicates variations in the energy and supply of dumped sediment, which are probably impacted by irregular shifts in the environment deposited. This argillaceous limestone is present in the Wargal Limestone sequence, indicating a dynamic and diverse sedimentary environment. Periods of enhanced siliciclastic input, probably from adjacent terrestrial sources, are interspersed with more normal carbonate deposition.

As it goes, comes to nodular limestone, which is identified by the presence of different fossils and its irregularly shaped nodules. There are fractures in this limestone that are connected to a minor fault, signifying that there has been tectonic activity close. The bedding style of this nodular limestone is characterized by varying dip angles, reflecting the influence of geological forces over time. Additionally, calcitic veins are visible, cutting through the limestone and filling fractures with crystalline calcite. These features suggest a complex depositional and diagenetic history, where biological, sedimentary, and tectonic processes have interacted to shape the current structure and composition of the rock.

Facies Description of Wargal Limestone having Facies in Nammal Gorge. A faulted anticline's north-eastern limb has a well-exposed piece of Wargal Limestone, which is part of Nammal Gorge (Fig. 4). Nevertheless, the lowest few meters in the anticline's centre are hidden. 154 meters measured thickness was investigated, compared to 146 meters reported by [11, 15]. The layers incline northeast. Turn left onto a dirt road towards Nammal Dam after driving past Musa Khel on the east side of Mianwali to reach the portion. The portion starts at the northwest side of the canyon, at the foot of the cliff. The depth of 154 meters revealed a colonial coral zone.

Wargal Limestone in Zaluch Nala. Teichert [16] surveyed and characterized the Wargal Limestone section at Zaluch Nala (Fig. 5). He designated it as a provisional standard until more research was done on the formation near the Wargal settlement, which he thought to be a suitable type locality. The formation is 174 meters thick overall, including the highest nodular beds. Teichert (1966) reported that 179 meters was the section's thickness. The slight variation in thickness is probably the result of different interpretations of the faulted portion located about 40 meters above the base. To get to

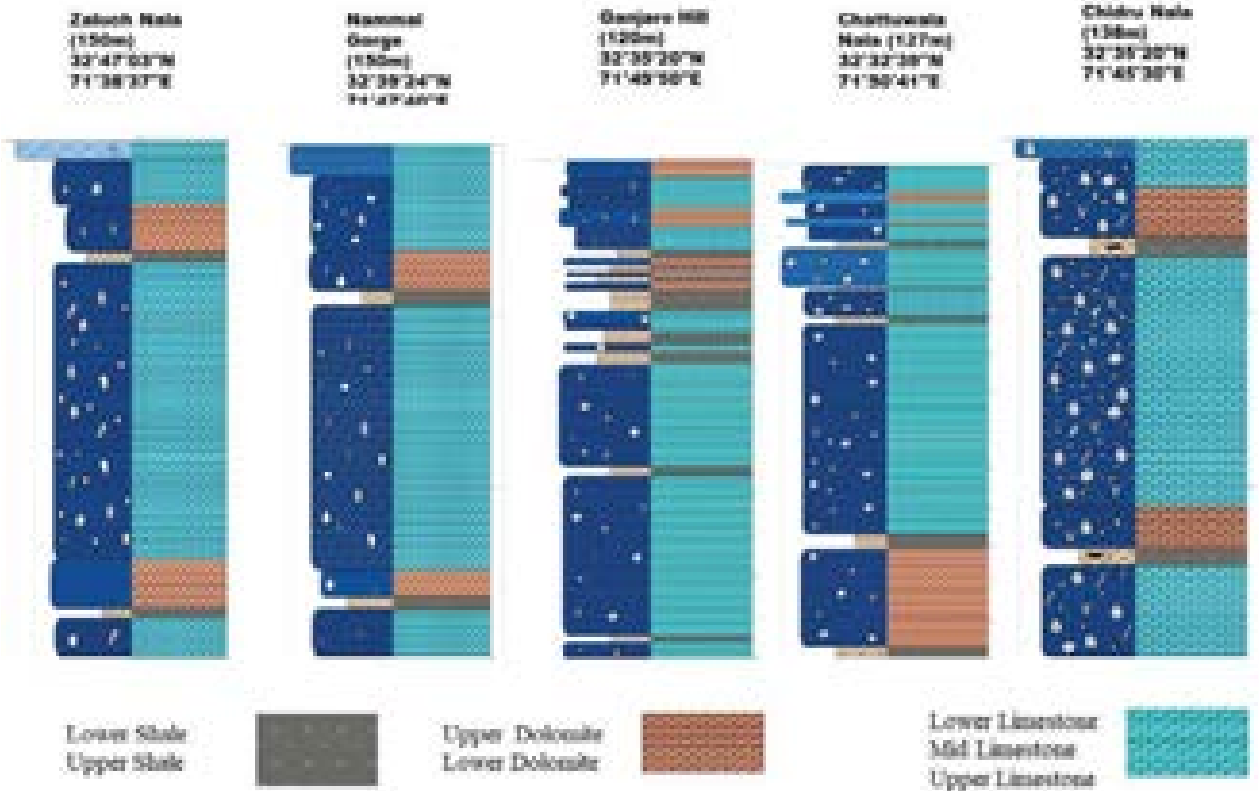


Fig. 4. Lithological logs of Wargal limestone at Nammal gorge, Zaluch nala, Chiddru, chattuwala nala and Ganjaro Hill, having the limestone, dolomite and shale. There are many fossils in these sections, including a large number of brachiopods, bryozoans, molluscs, crinoids, and other families

the part, take a car from Mianwali north to the village of Paikhel, and then drive east for about 10 km to Zaluch Nala. The east side of the canyon has the majority of the formation fully exposed, but only the upper on the west side of the canyon, nodular beds were measured.

Wargal limestone in Chiddru nala. The Chiddru Nala section, situated near Mianwali, Pakistan, provides a well-exposed outcrop of the Wargal Limestone on the northeast side of the nala, with the uppermost few meters covered by alluvial sediments (Fig. 6). The Chiddru Formation overlays the Wargal Limestone on the southwest side. At this location, the Wargal Limestone, including the upper nodular beds, is at least 130 meters thick, supporting the observation that the formation thins eastward through the Salt Range. To access the section, drive east from Mianwali, pass Musa Khel for approximately 5 kilometers, turn right onto a dirt road, proceed for 4 kilometers, turn right again, and continue for 1.5 kilometers. The section is located east of the road. This detailed examination aligns with [11] findings and highlights the geological significance and reservoir potential of the Wargal Limestone in the Salt Range.

Wargal Limestone in Chattuwala Nala. The Chattuwala Nala section, 6.5 kilometers northeast of Chiddru, is well exposed on the northeast side of the nala, though the upper few meters are covered by alluvial sediments (Fig. 5). The Chiddru Formation overlies the Wargal Limestone on the southwest side. The Wargal Limestone at Chattuwala is at least 130 meters thick, consistent with [11] observation of eastward thinning through the Salt Range. To access the section, drive east from Mianwali past Musa Khel for 5 kilometers, turn right onto a dirt road, proceed 4 kilometers, turn right again, and continue 1.5 kilometers. The section is east of the road. Two colonial coral zones were collected at 5.2 meters and 126.5 meters.

Wargal Limestone in Ganjaro Hill. The Ganjaro Hill section, 3 kilometers northeast of Chattuwala Nala, begins at the edge of a jeep road and extends up the hill (Fig. 5). The Wargal Limestone here is at least 124 meters thick. To reach it, drive east from Mianwali for 26 kilometers (5 kilometers past Musa Khel), turn right onto a dirt road, and continue southeast for 6.2 kilometers until the road ends. Walk 1.5 kilometers to the section base, starting just after the last zigzag. A colonial coral zone is at 14 meters.

Correlation. The Wargal Limestone within the salt range of Pakistan exhibits a variety of lithological units that changes throughout the different sections from Nammal to Ganjaro that shows prominent heterogeneity. Seven different units were identified after correlation; lower shale, upper shale, upper dolomite, lower dolomite lower, middle and upper Limestone units (Fig. 5). The sequences stratigraphy of these sections reveals both transgressive and regressive phases, which reflect fluctuations in sea level and offer a glimpse how Tethys Ocean evolved into

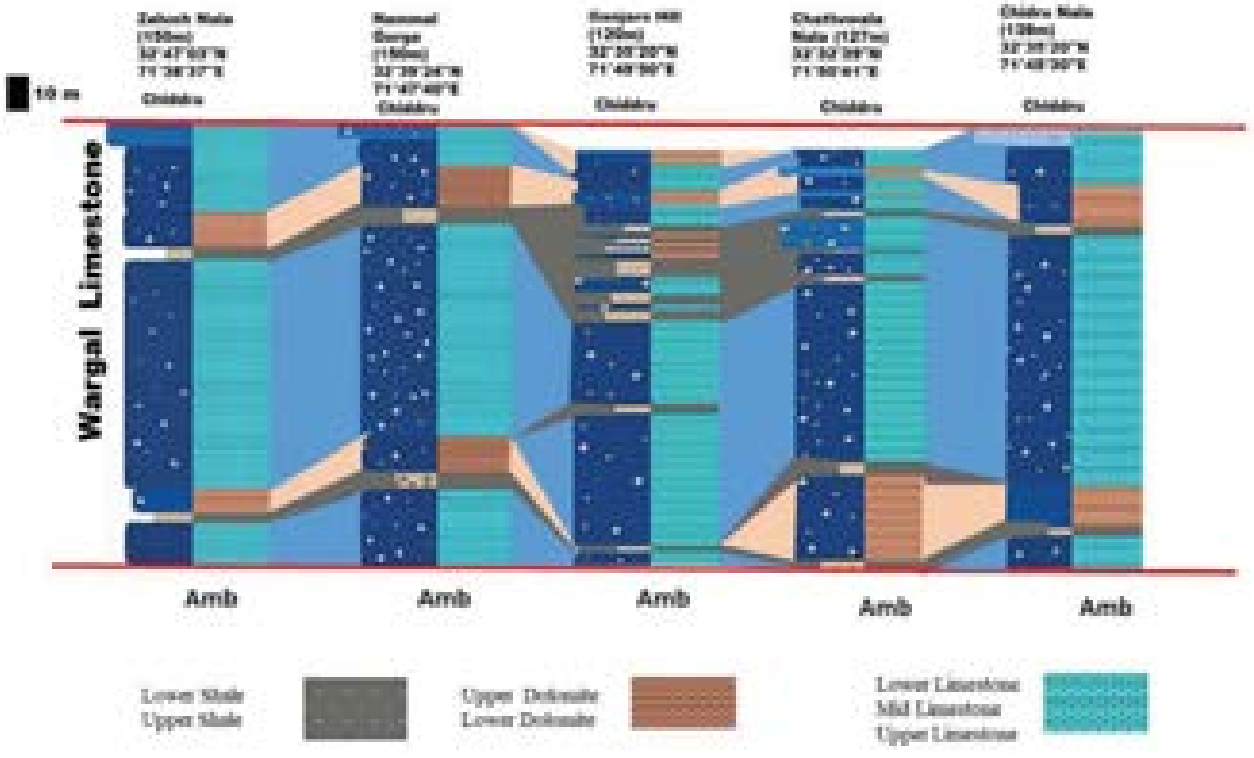


Fig. 5. Representative lithologs from the study outcrop sections showing vertical facies relationships, vertical scale in meters

fine carbonates sequences during Permian. In figure fossiliferous limestone interbedded porous dolomitic layers suggesting significant diagenetic alteration that could impact the reservoir quality. Additionally minor coal bearing shales are present. But advance research shows it is capable to hold reservoir of hydrocarbon.

Transgressive-regressive cycles of this formation are associated with relative rise and fall of sea level, which are important to sequence stratigraphy [13]. As a result of these cycles, hydrocarbon accumulation depends on the development of various sedimentary habitats, from shallow shelves to deeper basins. The trapping mechanisms created by these sequences, together with dolomitization, fossil content and carbonate phase development, set the stage for hydrocarbon reservoir potential. Understanding reservoir characteristics such as porosity and permeability requires understanding how the Wargal Limestone transformed from a siliciclastic-dominated unit to a carbonate-dominated unit. This transformation is reflected in changes in deposition energy.

Depositional model. The Wargal Limestone, which is mostly exposed in Salt Range Pakistan, is a significant carbonate sequence that was deposited between the Middle and Late Permian. This formation is well known for its varied depositional habitats, which represent a very active and varied marine system and vary from lagoonal to reefal settings (Fig. 6 and Table 2).

1. Lagoonal Environment: Lagoonal areas are typically located landward of coral reefs and are characterized by restricted circulation and poor energy conditions. The fine-grained micritic limestone found in the Lagoon Wargal sediments is most likely overlain by layers of dolomitic strata, indicating a period when water flow was restricted. This area is shown in the image by the dark blue section, which suggests a calmer, more sheltered depositional environment. Bone fragments, agglomerated foraminifera, and algae are typical of the fauna and sediment types found in this environment, and the lithology is dominated by fine-grained mudstone.

2. Reef Environment: The most dynamic and diverse parts of the sedimentary system are the reef facies. Reef structures serve as dividers between lagoon and open ocean habitats and were probably built from fragments of coral and bone. In the Wargal Limestone, bioclasts such

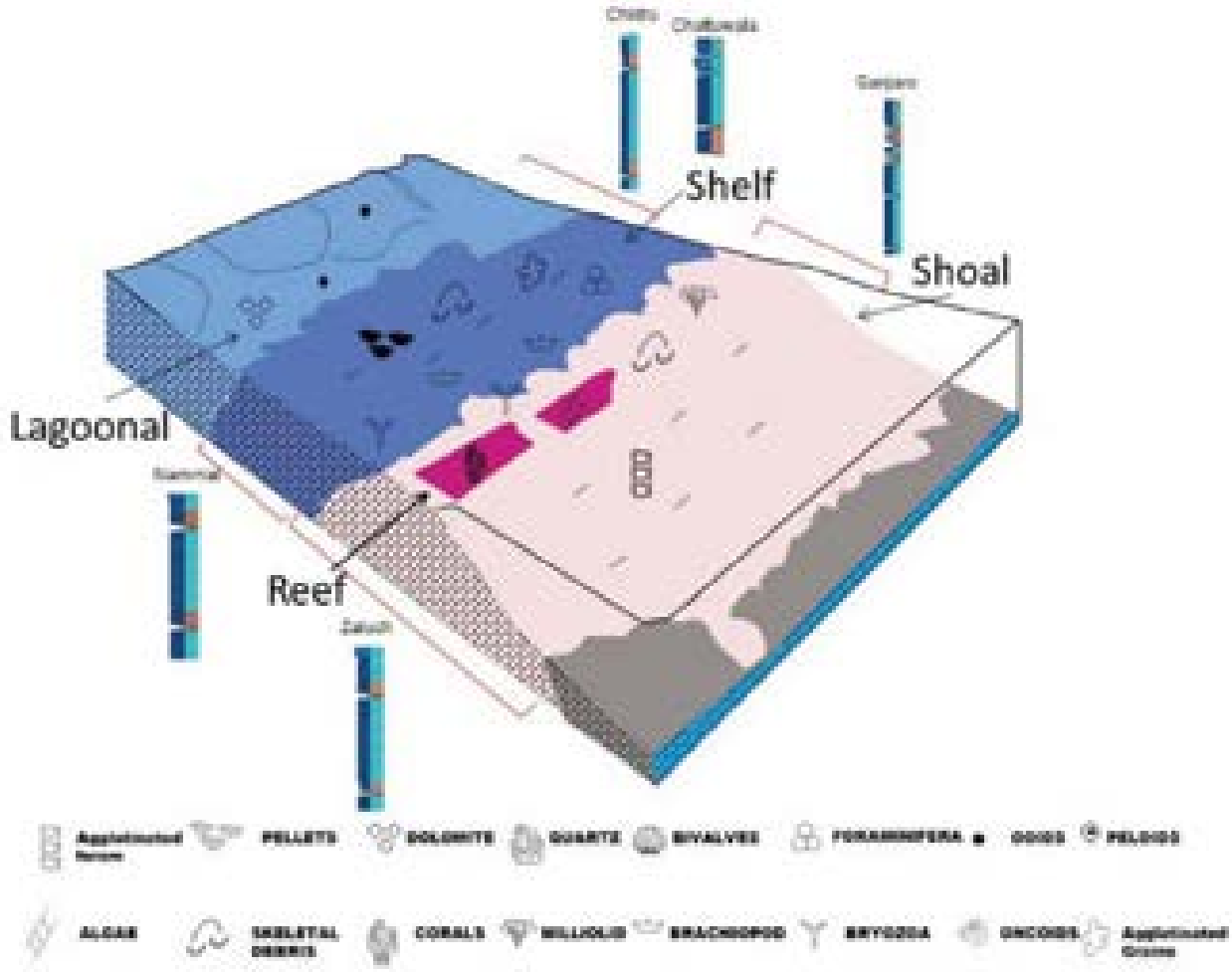


Fig. 6. Depositional Environment distribution across all five sections having fauna representation.

Table 2

Comparison of Wargal Limestone with other stratigraphic units in the Tethys Region

	Wargal Limestone Pakistan	Panjal Traps India	Chia Zairi Formation Iraq	Dalan Formation Iran	Gharif Formation Oman
Age	Middle to Late Permian (Guadalupian to Lopingian)	Early to Middle Permian (Cisuralian to Guadalupian)	Late Permian (Lopingian)	Late Permian (Wuchiapingian to Changhsingian)	Late Permian (Lopingian)
Lithology	Limestone with interbedded shale and dolomite	Basaltic lava flows with intercalated sedimentary layers	Limestone with minor dolomite and shale	Thick carbonate sequences with subordinate evaporites	Sandstone, siltstone, and shale with minor carbonate
Color	Light gray to gray	Dark gray to black	Pale gray to dark gray	Light gray to beige	Reddish-brown to gray
Thickness	150–200 m	500–800 m	200–250 m	300–400 m	300–350 m
Grain Types	Fine to medium-grained carbonates	Basaltic grains with interbedded clay	Micritic and bioclastic carbonates	Crystalline and oolitic carbonates	Dolomitic and fine-grained carbonates
Dominant lithofacies	Carbonate	Volcanic	Carbonate	Carbonate platform	Clastic
Depositional environment	Shallow marine shelf	Continental flood basalts	Shallow marine shelf	Shallow marine carbonate platform	Fluvial to shallow marine environments
Reservoir potential	Potential hydrocarbon reservoir	Limited reservoir potential due to volcanic nature	Potential hydrocarbon reservoir	Significant gas reservoirs, especially in the South Pars field	Significant oil reservoirs
Basinal distribution	Upper Indus Basin	Kashmir Basin	Northern Iraq	Zagros Basin	Interior Oman Basin
Paleogeography	Positioned at the northern margin of the Indian Plate during the Permian	Associated with the rifting of the northern margin of the Indian Plate	Situated on the northern edge of the Arabian Plate during the Permian	Part of the southern margin of the Paleo-Tethys Ocean	Deposited in fluvial to shallow marine settings on the eastern margin of the Arabian Plate

as bryozoans, brachiopods, and corals, which are abundant in the Permian carbonate system region, were often used to build coral reefs [1]. This Reef referred as a geo-body, that significantly present in area of Nammal Gorge and Zaluch Nala. The blue area between the lagoon and shoal in the figure represents the reef zone, which illustrates the energy transfer from a low-energy (lagoon) to a high-energy (shoal) ecosystem (Fig. 6).

3. Shoal Environment: The higher energy conditions known as shoals are where coarse-grained material is deposited. The shoal deposits in the Wargal Limestone will consist of ooids, peloids and oncoids, limestones supported by grains [13]. This setting is represented by the pink to light area in the diagram. Oolitic limestone is common here, with characteristics such as large grain size and cross-bedding. This habitat is defined by tidal currents and wave action, which continuously transform the sediments.

4. Shelf Environment: The continental shelf is an example of a shallow marine environment, susceptible to tides and waves, and is usually relatively open. More granular limestone mixed with quartz and bioclasts may have been deposited on the shelf of the Wargal Limestone [14]. This depositional environment represented by the lightest pink area in the image, which moves outward and toward deeper marine environments. The area affected by scattered storms and tempests.

Discussion. Facies studies of the Wargal Limestone and correlations between the Nammal Gorge, Zaluch Nala, Chiddru Nala, Chattuwala Nala and Ganjaro Hill sections provide important new information on the Late Permian sedimentary dynamics and sedimentation environment of the Tethyan region. Each section exhibits a unique lithological composition, reflecting the varying depositional environments across the Pakistan Salt Range. Several different lithofacies are found in the Wargal limestone, such as shale, dolomite, sandy limestone and fossiliferous limestone. For example, the Nammal Gorge area is composed of dolomite (10%), sandy limestone (12%), and limestone (56%). In the Zaluch Nala and Chiddru Nala areas, shale and dolomite formations are interbedded with limestone. Nine different lithofacies, with support ranging from mud-supported to grain-supported, illustrate the depositional changes in the formation. Different sedimentary energy and environmental conditions in different periods are reflected in changes in particle size, fossil content and diagenesis of different phases.

Correlation of these sections shows stratigraphic continuity but with some obvious changes in

lithology and thickness. For example, the thickness varies from 150 meters at Nammal and Zaluch to about 130 meters at Chiddru and Chattuwala. Chattuwala has a higher proportion of dolomitic limestone (75%) than Nammal and Zaluch. These differences show differences in sea-level fluctuations during deposition, tectonic effects, and sediment supply in different areas. The depositional habitat of the Wargal Limestone is primarily marine, ranging from lagoons to coral reefs and shoal environments. Fossil assemblages such as corals, molluscs, brachiopods and bryozoans indicate the presence of a strong marine environment [13]. Interbedded dolomite, limestone, and shale show periods of restricted circulation and salinity fluctuations that characterize the transition from lagoon habitat to an open marine environment. Changes in sea level are reflected in the strata through transgression-regression cycles, thereby affecting sedimentary facies.

In order to establish a thorough depositional model, the phase distribution and correlation of these sections are critical and have implications for hydrocarbon development [21, 23]. The presence of fossiliferous limestone and porous dolomitic layers suggests that diagenesis improved reservoir quality. The tectonic and climatic environment that formed the salt range during the Permian period can be understood from the observed heterogeneity in depositional patterns.

The formations of the Wargal Limestone exhibit important transgressive-regressive cycles that are driven by changes in sea level and may be influenced by tectonic activity or global climate change. The transition from low-energy lagoon deposition to high-energy reef-flat habitats is characterized by periodic shallowing and deepening phases, which regulate sediment accumulation from siliciclastic-dominated phases to carbonate-rich phases [8].

Fossil limestone and dolomite dominate the carbonate lithofacies, indicating deposition in a shallow marine environment. Fossils are abundant, indicating the presence of powerful marine life in stable shallow waters, creating bioclast-rich reef and shoal facies in a high-energy environment of currents and wave action [14].

Folds and faults seen in the outcrop show that tectonic forces were the primary factor in the deposition of the Wargal Limestone. The distribution and thickness of limestone units are determined by compressional structures, which also play a role in diagenetic processes such as dolomitization, altering permeability and porosity. Older strata were also exposed by tectonic uplift, which helped provide sediment during the formation of the Wargal Limeston**e.**

The initial appearance of the Wargal Limestone has changed due to diagenetic processes such as dolomitization and the production of chert dolomite. These changes result in improved reservoir quality of the rock and are primarily caused by changes in secondary porosity as well as pore water chemistry, compaction and tectonic stress. The different phases, diagenetic changes and structural style of the Wargal Limestone make it a promising source of hydrocarbons. Dolomitization and fossil dissolution improve the reservoir quality of porous dolomitic formations, especially in Chattuwala and Ganjaro. Interbedded dolomite, shale, and limestone can also create stratigraphic traps containing hydrocarbons. Fossil limestone, rich in bioclasts, has high porosity because dissolution of skeleton component. This provides an optimal environment for hydrocarbon migration and trapping, combined with secondary porosity created by diagenesis. Certain sections have fractures and calcite-filled veins that increase permeability and facilitate fluid movement. The tectonic setting of the Salt Range creates the structural traps necessary for hydrocarbon accumulation. Folds and faults in the Wargal limestone may have been effective in trapping hydrocarbons within porous dolomitic units. Due to stratigraphic changes between sections, there is an opportunity to find sealed reservoirs for possible hydrocarbon extraction.

Conclusion

The combined facies analysis indicates the Wargal Limestone was deposited in various shallow marine environments, from inner ramp to middle-ramp settings, which reflects dynamic paleoenvironmental conditions controlled by relative changes in sea level along the Paleotethys margin. Extensive stratigraphic correlation across multiple outcrop sections provides evidence for lateral facies continuity and supports a uniform regional depositional framework, which enhances the comprehension of the space-time evolution of carbonate systems in the Permian.

The integration of facies architecture, sedimentary structures, and fossil content is useful in revealing the paleoenvironmental conditions and tectonic stability of the northern Gondwanan shelf and making contributions to more general reconstructions of the Paleotethys paleogeography.

In the end, studies of facies and sedimentation environments of the Nammal, Zaluch, Chiddru, Chattuwala and Ganjaro sections provide important insights into the stratigraphy of the Wargal limestone. Correlations are needed to grasp the depositional history and reservoir potential of the area, which indicate major lateral phase changes and reservoir potential, as evidenced by its depositional history. Due to its various facies, particularly fossiliferous limestone and porous dolomite formations, and its structural location within a salt range, the formation is a viable target for hydrocarbon development.

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Внесок авторів: всі автори зробили рівний внесок у цю роботу
Конфлікт інтересів: автори повідомляють про відсутність конфлікту інтересів
Декларація про використання генеративного штучного інтелекту: автори підтверджують, що під час підготовки рукопису не використовувалися інструменти штучного інтелекту.

Authors Contribution: All authors have contributed equally to this work
Conflict of Interest: The authors declare no conflict of interest

Declaration of use of generative artificial intelligence: The authors confirm that no AI tools were used during the preparation of the manuscript.

Інтегрований фаціальний аналіз і стратиграфічна кореляція варгальського вапняку: аналіз даних відслонень і середовищ осадження вздовж Палеотетису

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АНОТАЦІЯ

Це дослідження має на меті вивчити фації та середовище відкладень пізнього пермського вапняку в басейні Верхнього Інду шляхом характеристики геологічних і мінералогічних зразків порід, зібраних з різних місцевостей. Геотіла та осадову архітектуру вапняку Варгал розшифрували за допомогою польових спостережень. Методи досліджень – фаціальний аналіз, стратиграфічний каротаж і літологічна кореляція, які були використані для інтерпретації даних відслонень і реконструкції середовища відкладення. На основі скам›янілостей, наявних у літофаціях, розроблено середовище його відкладення. Седиментологію вивчали за допомогою вимірювання розрізів разом із польовими фотографіями високої розподільної здатності, які були зібрані з використанням неоднорідності фацій та архітектури. Потім фації були нанесені на польові фотографії високої розподільної здатності. Згенерований набір даних включає седиментологічні журнали, зразки та польові фотографії для забезпечення відтворюваності та майбутніх порівняльних стратиграфічних досліджень. Поширені фації вуглистих сланців, піщаних вапняків, глинистих вапняків, викопних вапняків і доломітових вапняків. Скам›янілості, такі як мшанки, плеченогі молюски, двостулкові молюски, черевоногі молюски та трилобіти, датують його середньо-пізнім пермським періодом. П›ять секцій варгальського вапняку були взяті для кореляції. Бічні зміни цих фацій показують стратиграфічну безперервність, але з деякими очевидними змінами в літології та товщині. Через стратиграфічні варіації існує можливість виявити зоновані резервуари для потенційного видобутку вуглеводнів. Різноманітні середовища відкладення цієї формації, які варіюються від лагунних до рифових, широко відомі тим, що представляють дуже активну та різноманітну систему палеотетису. Дослідження підтримує Ціль сталого розвитку (ЦСР) 9 шляхом поглиблення геологічних знань, пов'язаних з оцінкою ресурсів та аналізом осадових басейнів, а також ЦСР 13 – шляхом покращення розуміння клімату та найдавніших умов навколишнього середовища. Оскільки формація складається з різних типів порід, включаючи скам'янілий вапняк і пористий доломіт, і оскільки вона розташована в соляному хребті, вона має хороший потенціал для розвідки нафти і газу в прилеглих басейнах Потвар, Кохат і Банну. Результати цього дослідження рекомендовані для аналогів як керівництво при розробці основи для майбутніх досліджень порівнянних карбонатних порід у досліджуваному регіоні.

ІНФОРМАЦІЯ ПРО СТАТТЮ:

Рукопис надійшов
27 листопада 2025

Отримано після рецензування
13 січня 2026

Затверджено до друку
25 травня 2026

Опубліковано онлайн
30 травня 2026

Ключові слова:

літофації, лагуна, рифи, кореляція, варгальський вапняк, геотіла, резервуар, динаміка басейну, коливання рівня моря, осадова архітектура, ЦСР 9, ЦСР 11.

https://doi.org/10.26565/2410-7360-2026-64-03
UDC 553.98:552.5:550.4

Provenance and petroleum potential of oil-bearing rocks in the Beridash field (Southern Gobustan, Azerbaijan): A mineralogical and geochemical assessment

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ABSTRACT

This research presents a complex formational analysis of the extensively exposed Lower Pliocene Productive Series (PS) unconventional reservoir rocks in the Beridash field (Southern Gobustan, Azerbaijan). Utilizing lithological, mineralogical, and geochemical proxies, the study assesses their sedimentary environment, provenance, and petroleum potential, emphasizing the mineralogical control on hydrocarbon accumulation.
Problem statement: Despite Azerbaijan's extensive conventional hydrocarbon extraction, unconventional oil-bearing surface exposures remain geologically underexplored. A comprehensive formational, mineralogical, and geochemical characterization is required to determine the primary factors controlling hydrocarbon enrichment within these specific stratigraphic units.
Purpose: This research aims to delineate the provenance and hydrocarbon potential of the Beridash field through an integrated mineralogical and geochemical assessment, with a specific focus on the mechanisms controlling oil enrichment.
Methods: The analytical methodology integrated detailed surface mapping, mineralogical characterization via X-ray diffraction (XRD), and geochemical assessment of major

ARTICLE INFO

Manuscript received
24 October 2025

Revised manuscript received
8 April 2026

Manuscript accepted
25 May 2026

Available online
30 May 2026

In cites: Baloglanov Elnur, Yolchuyeva Ulviyya, Khuduzade Arastun, Muradova Peri, Akhundov Ruslan, Jafarova Rena, Samedov Elmar (2026). Provenance and petroleum potential of oil-bearing rocks in the Beridash field (Southern Gobustan, Azerbaijan): A mineralogical and geochemical assessment. *Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology*, (64), 32–48. https://doi.org/10.26565/2410-7360-2026-64-03



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oxides using X-ray fluorescence (XRF) and ICP-MS. Oil content was calculated gravimetrically following moisture correction.

Results: Detailed surface mapping identified eight distinct, predominantly calcareous oil-bearing sand and sandstone units localized within the 1245-1480 m stratigraphic interval from the top of the Lower PS. Mineralogically, the rocks represent a mixed carbonate-terrigenous sequence dominated by calcite (avg. 24.97%) and quartz (avg. 23.57%), alongside clay minerals. Geochemical proxies indicate deposition in a shallow marine-lagoonal environment along an active continental margin from mixed felsic and mafic sources. The average oil content is 7.64%, increasing from northwest to southeast. A weak correlation (r = 0.02) between moisture (avg. 1.14%) and oil saturation demonstrates that mineralogy, specifically the ratio of fluid-blocking clays to brittle minerals, acts as the primary control on hydrocarbon accumulation.

Conclusions: Based on extensive surface mapping, the eight delineated calcareous sand and sandstone units represent a highly promising non-conventional hydrocarbon resource. Their specific provenance has produced a mineralogical framework highly conducive to hosting hydrocarbons, functioning largely independent of moisture influence. These findings provide a robust formational evaluation model for regional non-conventional resources.

Keywords:

Azerbaijan, Productive Series, oil-bearing rocks, mineralogy, geochemistry, provenance, oil enrichment, moisture, petroleum potential.

Introduction and current state of research

Given the declining dynamics of Azerbaijan's nearly two-century-old conventional oil and gas production, attention has increasingly shifted toward unconventional hydrocarbon resources [11-13; 15; 28; 30; 32; 41; 45; 46]. In this regard, oil shales and oil-bearing rocks, exhibiting substantial prospective resources across more than a hundred surface exposures, are of particular importance [2; 3; 8-10; 36]. In recent years, based on complex geological, mineralogical, and geochemical studies, extensive research has been conducted not only on the genesis of oil shales but also on the potential for obtaining synthetic hydrocarbons (shale oil and shale gas) from kerogen-rich sediments of low thermal maturity [1; 4]. However, except for a few recent studies [e.g., 19], oil-bearing rocks remain poorly investigated. Previous works have primarily focused on the geological characteristics of oil bearing areas, including the evaluation of effective reservoirs and the preliminary study of certain physicochemical parameters of the rocks [5; 7; 37; 43]. Nevertheless, the provenance of these heavy hydrocarbon-bearing sediments that evolved from the Miocene to the Pliocene, and particularly the factors controlling hydrocarbon enrichment, have been insufficiently assessed compared to countries such as Canada and Venezuela, where this field is considerably more advanced [22; 26; 27; 44].

The present study, for the first time, investigates the formation conditions and hydrocarbon potential of oil-bearing rocks widely exposed at the surface within the Beridash area of the Shamakhi-Gobustan oil-gas-bearing region in Eastern Azerbaijan, based on comprehensive geological, mineralogical, and geochemical analyses.

Geological framework of the study area.

The location of Eastern Azerbaijan within the collision zone of the African and Arabian plates facilitated the accumulation of organic-rich sediments (mainly from the Middle Eocene to the Upper Miocene), their transformation into hydrocarbons, and the vertical migration of these hydrocarbons, which primarily accumulated in the productive Pliocene deposits, particularly creating favorable conditions for the formation of mud volcanoes [14; 16-18; 20; 21; 34; 39; 40]. Tectonic activity provided conditions for the uplift of layers composed of immature source rocks (mainly oil shales) and hydrocarbon-bearing sediments to the surface across tectonic zones with varying geological settings. Such zones generally differ significantly in terms of the size and activity of mud volcanoes.

The Beridash area, identified within the southern segment of Eastern Azerbaijan, is characterized by numerous oil-bearing outcrops extending southeastward from the Durandagh mud volcano toward the Gotur mud volcano (Fig. 1). Historically, based on extensive surface mapping supplemented by shallow exploratory pitting and trenching, the Beridash area has been classified and documented as a distinct oil-bearing field in classical regional geological literature [5-7; 42]. Given the current absence of deep exploratory wells, the structural geometry of the area is primarily delineated through these surface investigations.

From a tectonic perspective, the Beridash structure is situated along a major anticlinal axis identified in the Gobustan region [7]. This tectonic feature, known as the Alat Ridge, separates two structural zones – Gobustan and Southeastern Shirvan. Along this tectonic line, several anticlines such as Alat, Dashgil-Dilangaz, Gyrdagh, Goturdagh, Ayrantoken, and Solakhay have been identified, most of which are characterized by numerous oil-bearing outcrops.

Structurally, the northwest-southeast trending Beridash structure is oriented almost transversely, forming the western undulation of the Alat Ridge anticlinal line. Similar to other structures along this ridge, Beridash is markedly

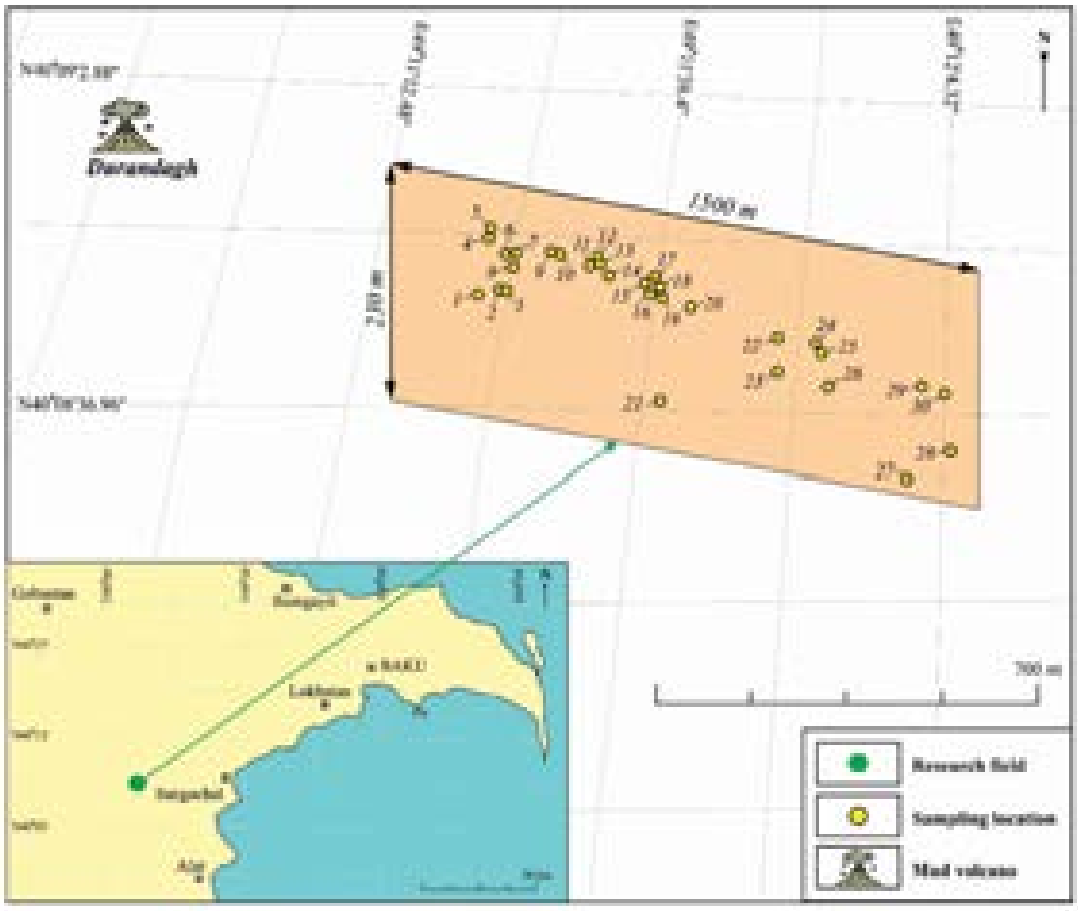


Fig. 1. Location map of study areas

asymmetric: its northern limb dips at angles of 40-60°, while the southern limb is steeply inclined, reaching angles of 80-85°, and is prone to overturning in several areas. The oil-bearing rocks of Beridash, constrained by the Alat Ridge to the northwest, are associated with several tectonic dislocations. The most prominent of these occurs on the northern limb of the structure, characterized by a significant downthrow of 100-120 m. Associated with these structural features, the exposed sequence comprises multiple parallel oil-bearing beds. As documented in historical records, these strata are specifically localized in the lower part of the Productive Series section, within the interval of 1245-1480 m from its roof. Within this specific package, the most massive and significant hydrocarbon accumulations are distinguished primarily by their considerable thickness.

The geological structure of the area, mapped as a surface representation of the formational boundaries, comprises the PS and Aghchagil deposits of the Pliocene, as well as Quaternary sediments (Absheron and Lower Caspian) and mud-volcano breccias (Fig. 2).

Lower Pliocene PS deposits associated with oil-bearing rocks are exposed on both limbs of the anticline, including its crest. These deposits consist mainly of clays, sands, and siltstones. Overall, the Pliocene strata that host hydrocarbons in the uplifted zone have undergone extensive erosion. The thickness of the PS in this area ranges from 1500 to 1800 m. The Aghchagil deposits are observed along a relatively narrow belt, with thicknesses varying between 50 and 60 m. They are characterized by an alternation of gray clays and sands. The Absheron deposits, together with the lithofacies of the Lower Caspian, are exposed on the southern limb of the anticline. These sediments, composed of limestones, sands, and clays, generally do not exceed 60 m in thickness. Additionally, a prominent layer of mud-volcano breccia, reaching a thickness of 50-60 m, is widely distributed at the base of the localized sections.

Exposures of oil-bearing rocks

Field investigations conducted over an area of 62 hectares identified extensive surface outcrops of oil-bearing rocks beginning approximately 700 m southeast of the Durandagh mud volcano's crater zone.

In the lower exposed part of the PS, a 221.9 m thick section comprising 27 alternating layers has been identified, characterized by a frequent and monotonous interbedding of clays, sands, silts and

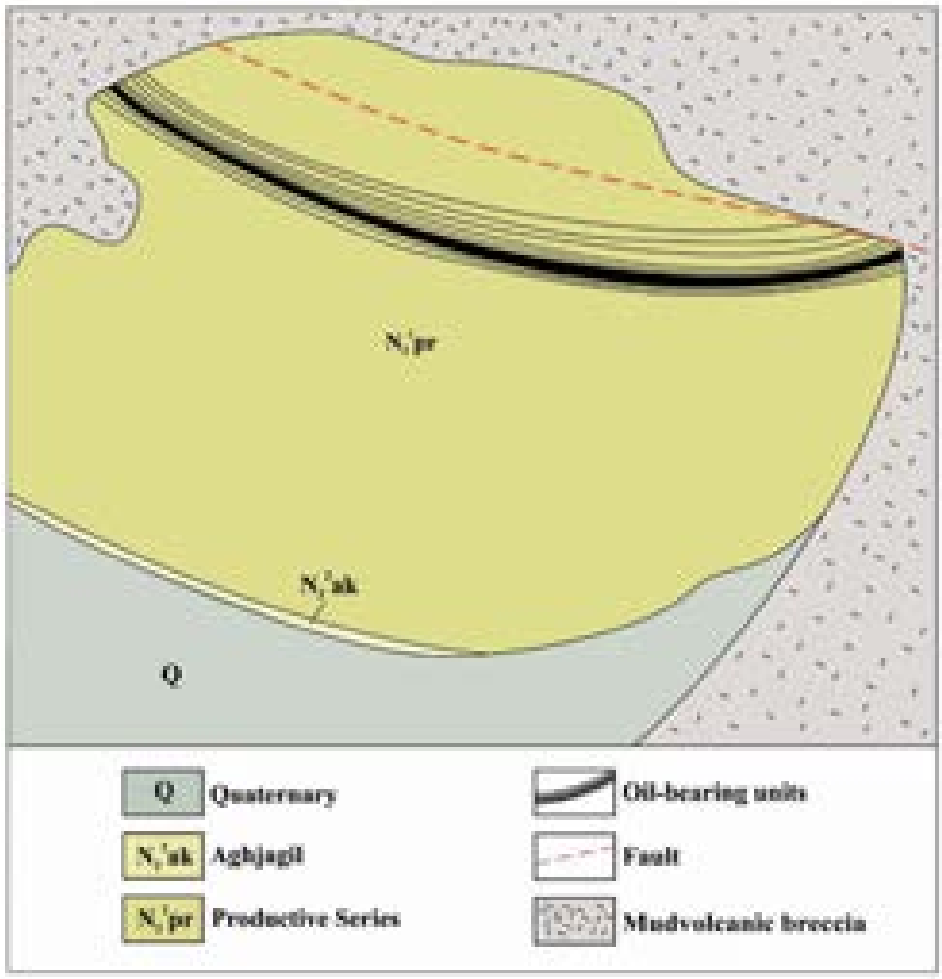


Fig. 2. Surface geological map of the Beridash area, illustrating the distribution and formational boundaries of the Lower Pliocene PS, the main tectonic fault, and prominent outcrops of the oil-bearing strata (modified from [43])

sandstones. While the overall sequence maintains a predominantly clayey character, the sandy and silty lithotypes within this section exhibit a distinctly calcareous composition. Within this sequence, specifically localized in the stratigraphic interval between 1245 m and 1480 m from the top of the PS, eight primary oil-saturated units, separated by predominantly clayey and silty inter-layers, are delineated (Fig. 3) [43]. These units possess a cumulative thickness of 57 m and demonstrate remarkable lateral persistence for up to 1 km.

Visually, Unit 1 and Unit 2 consist of brown, fine-grained sandstones. Unit 3 and Unit 4 are represented by brownish-grey and brown, fine-to-medium grained sands. Notably, Unit 3 exhibits the most pronounced visual oil saturation and thickness, with individual oil-saturated layers in this part of the section reaching up to 26 m (Fig. 4). The sequence continues with Units 5, 6, and 7, which are dominated by brownish-grey to brown, fine-grained, loose sands, and is terminated at the base by Unit 8, identified as a brownish-grey, and poorly sorted sandstone. Overall, despite their primary colors, many of these units appear dark brown to nearly black in the field due to heavy oil impregnation and surface bitumen tarring. The base of the entire exposed sequence is marked by a massive, 150-170 m thick clay-shale package, which contains thin (0.3-0.5 m) lenses and interlayers of fine-grained sand and sandstone [43].

Samples and analyzes

Thirty oil-bearing rock samples were collected from the study area for analytical investigation (Fig. 1), with select visual characteristics presented in Table 1.

Chemical composition was analyzed using both an S8 TIGER Series 2 and an Agilent 7700 Series ICP-MS, while mineralogical characteristics were determined using a MiniFlex 600 X-ray diffractometer.

The oil content was determined by gradual heating of the samples in an oven and calculated from the total weight loss after moisture correction, following the procedure described by [25].

Sample moisture was measured by oven drying in the same institute according to ASTM D2216.

Table 1

Visual characteristics of selected oil-bearing rock samples

Sample	Image	Description
B-5		Carbonate-sandy rock with low clay content. Emits a weak oil odor
B-7		Carbonate-sandy rock showing an oil scent
B-12		Carbonate-sandy rock exhibiting higher oil saturation
B-19		Light-colored carbonate-sandy rock with a weak oil scent
B-25		Carbonate-bearing sandstone, readily splitting along parallel surfaces and exhibiting a pronounced oil
B-30		Poorly compacted carbonate-sandy rock with a detectable oil scent

Mineralogical analysis

Eight minerals from different classes were identified (Table 2). Among silicates, quartz accounts for an average of 23.57%, while feldspars average 15.6%. The carbonate fraction is dominated by calcite, with a mean concentration of 24.97%. Clay minerals, including montmorillonite (9.6%), kaolinite (8.3%), and illite (4.43%), collectively comprise an average of 22.33% of the samples. Other components include hematite (6.3%) and gypsum (0.23%). Overall, the mineral distribution in terms of concentration follows the order: calcite > quartz > feldspar > montmorillonite > kaolinite > hematite > illite > gypsum.

Mineralogical classification indicates that, due to the high content of calcite (see Table 2), the studied rocks are not exclusively siliceous but also exhibit a tendency toward carbonate lithotypes (Fig. 5).

Major oxides

Based on chemical composition analysis, the samples contain average concentrations of 44.77% SiO_2, 9.98% Al_2O_3, 6.75% Fe_2O_3, 16.22% CaO, 2.03% Na_2O, 1.68% K_2O, 2.34% MgO, 0.19% MnO, 0.52% SO_3, 0.72% TiO_2, 0.15% P_2O_5, 0.11% BaO, and 0.08% SrO (Table 3). The following abundance sequence of major oxides is established: Si > Ca > Al > Fe > Mg > Na > K > Ti > S > Mn > P > Ba > Sr

Provenance

The observed mineral assemblage, dominance of calcite, substantial quartz and feldspar, plus clay minerals such as montmorillonite, kaolinite, and illite, with minor hematite and gypsum (see Table 2), is consistent with deposition in a shallow marine-lagoonal environment under oxidizing, low-to-moderate weathering conditions [e.g., 48; 49].

The positioning of the samples in the Wacke – Shale – Fe-shale range on the log (Fe_2O_3/K_2O) vs. log (SiO_2/Al_2O_3) diagram (Fig. 6A) indicates a mixed provenance with moderate chemical weathering. It suggests contributions from both felsic and mafic sources, reflecting an intermediate tectonic setting. Furthermore, the geochemical classification diagram based on log (Na_2O/K_2O) vs. log (SiO_2/Al_2O_3) (Fig. 6B) shows their location at the intersection of the Greywacke and Litharenite fields, reflecting

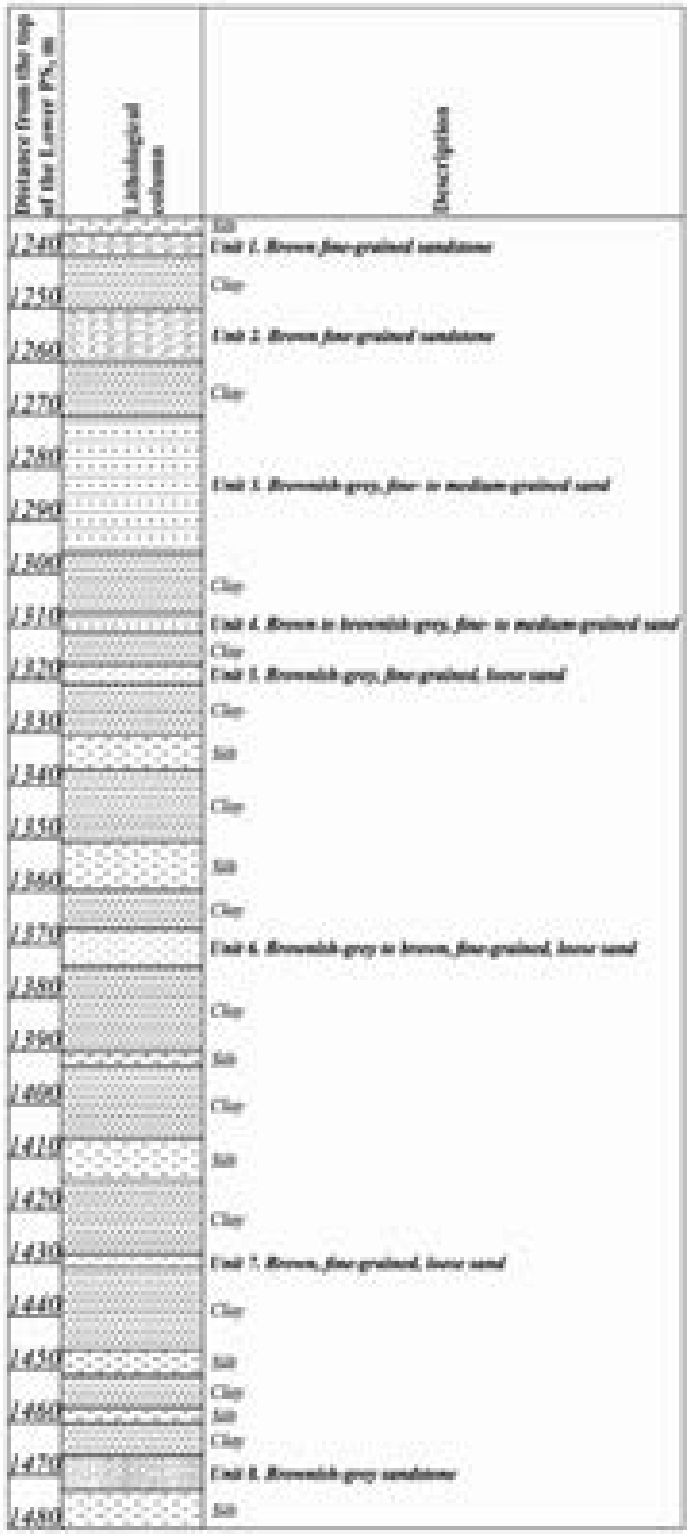


Fig. 3. Lithological-stratigraphic column of the Lower Pliocene Productive Series (PS) oil-bearing sequence at the Beridash area, showing the eight primary units identified within the 1245-1480 m interval from the top of the PS [43]

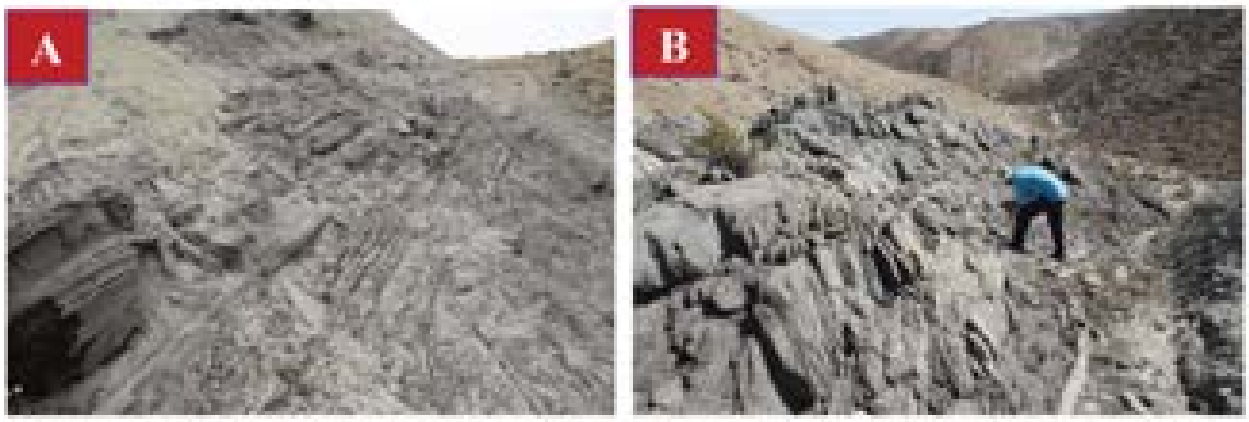


Fig. 4. Field photographs showing the surface exposures of the principal, massive oil-bearing stratum in the Beridash area

Table 2

Mineralogical characteristics of the samples (%)

Sample	Quartz	Feldspar	Calcite	Montmorillonite	Kaolinite	İllite	Hematite	Gypsum	Other mineral components
1	26	18	21	9	8	5	6	0	2
2	25	17	23	9	7	5	7	0	2
3	24	14	26	9	9	5	6	0	2
4	25	14	25	9	9	5	6	0	2
5	22	16	32	8	7	5	3	0	2
6	20	15	28	10	8	5	7	0	2
7	24	14	26	9	9	5	6	0	2
8	24	15	25	10	8	5	6	0	2
9	22	16	24	11	9	5	6	0	2
10	23	15	27	9	8	5	6	0	2
11	24	16	25	7	9	5	7	0	2
12	20	14	28	10	7	3	11	0	2
13	37	15	14	11	8	3	5	0	2
14	22	20	27	8	8	3	5	0	2
15	24	17	20	10	10	5	7	0	2
16	21	15	30	9	8	3	7	0	2
17	20	15	25	9	10	6	8	0	2
18	27	15	24	11	8	3	5	0	2
19	28	17	22	10	8	3	5	0	2
20	23	15	29	8	7	5	6	0	2
21	24	18	23	11	8	3	6	0	2
22	24	14	24	10	10	5	6	0	2
23	21	17	28	9	8	3	7	0	2
24	22	15	26	9	8	5	8	0	2
25	22	17	25	10	7	5	7	0	2
26	22	16	25	10	9	5	6	0	2
27	21	15	21	9	9	5	6	7	2
28	25	14	25	9	9	5	6	0	2
29	22	15	25	12	8	5	6	0	2
30	23	14	26	13	8	3	6	0	2

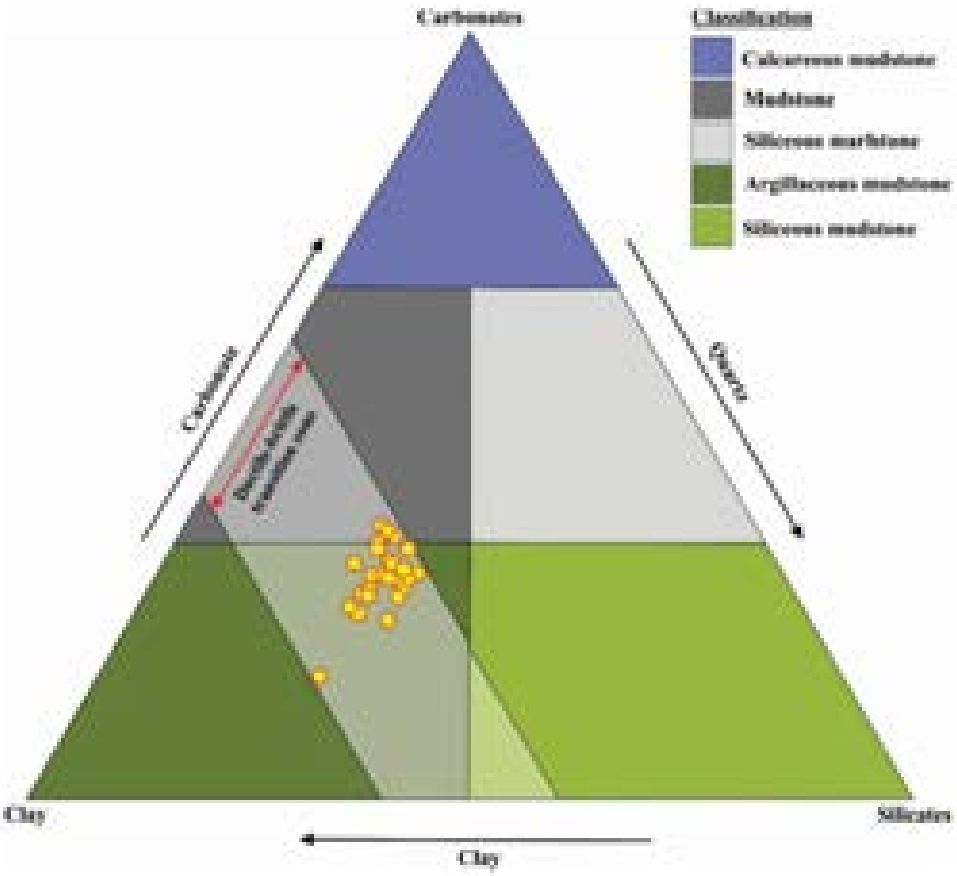


Fig. 5. Mineralogical classification of oil-bearing rock samples, showing the ductile-brittle transition zone as a mix of clay, quartz, and carbonate [4; 19]

Table 3

Concentrations of major oxides in the samples (%)

Sample	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	Fe_2O_3	BaO	SrO
1	3.37	2.92	10.34	47.57	0.18	0.28	1.65	13.25	1.05	0.25	6.56	0.09	0.06
2	2.25	2.81	10.55	46.92	0.18	0.27	1.76	15.66	0.65	0.18	7.08	0.12	0.08
3	2.17	2.34	9.52	43.98	0.13	0.21	1.53	19.36	0.56	0.22	6.25	0.09	0.07
4	2.20	2.63	9.70	44.66	0.16	0.52	1.66	15.42	0.73	0.21	6.28	0.12	0.07
5	2.26	1.33	8.24	41.26	0.13	0.39	1.28	25.36	0.42	0.23	3.66	0.01	0.06
6	2.12	2.26	10.03	43.46	0.17	0.51	1.59	15.13	0.82	0.15	7.88	0.10	0.08
7	1.73	2.18	9.71	44.31	0.14	0.56	1.72	17.06	0.64	0.18	6.66	0.11	0.09
8	2.07	2.12	9.68	45.62	0.16	0.58	1.75	16.14	0.59	0.18	6.58	0.07	0.08
9	2.38	2.32	10.44	45.91	0.16	0.42	1.66	15.82	0.71	0.17	6.72	0.07	0.07
10	1.88	2.20	10.03	43.49	0.14	0.42	1.68	16.30	0.99	0.18	6.29	0.09	0.08
11	2.37	2.27	10.16	44.45	0.17	0.54	1.56	16.59	0.77	0.18	7.90	0.07	0.07
12	2.04	2.37	8.94	39.32	0.15	0.44	1.43	16.40	0.65	0.21	11.12	0.09	0.08
13	3.14	1.87	10.53	56.36	0.14	0.39	1.79	9.23	0.53	0.13	5.17	0.10	0.07
14	1.91	2.19	10.06	44.41	0.15	0.40	1.79	16.71	0.63	0.18	5.86	0.11	0.08
15	1.67	2.00	10.48	46.87	0.16	0.58	1.85	12.37	0.63	0.17	7.35	0.10	0.08
16	1.55	2.24	9.74	42.59	0.16	0.28	1.66	18.01	0.71	0.23	7.06	0.10	0.07

Continuation Table 3 / Продовження Таблиці 3

17	1.73	2.35	10.01	42.02	0.16	0.58	1.61	16.72	0.94	0.21	8.27	0.08	0.08
18	1.73	2.31	10.73	46.13	0.15	0.38	1.86	14.39	0.69	0.15	5.77	0.11	0.08
19	2.33	2.25	10.48	47.51	0.14	0.66	1.92	13.89	0.69	0.14	5.60	0.09	0.07
20	1.75	2.27	9.35	42.55	0.15	0.43	1.63	20.16	0.68	0.21	6.33	0.06	0.09
21	1.93	2.05	10.18	46.18	0.13	0.62	1.82	13.99	0.61	0.16	6.22	0.19	0.09
22	1.60	2.98	10.01	45.07	0.17	0.32	1.70	16.86	0.73	0.20	6.97	0.01	0.08
23	1.76	1.92	9.18	41.69	0.11	0.56	1.71	16.41	0.79	0.18	7.03	0.18	0.09
24	1.92	3.04	10.09	42.12	0.16	0.22	1.49	17.13	1.18	0.19	8.34	0.07	0.07
25	2.01	3.08	10.20	44.34	0.12	0.33	1.68	17.05	0.78	0.21	7.18	0.08	0.08
26	2.25	2.81	10.29	43.93	0.17	0.29	1.66	18.01	0.58	0.22	6.21	0.06	0.06
27	1.64	2.56	9.70	42.95	0.15	3.02	1.74	17.44	0.59	0.17	6.18	0.01	0.09
28	1.86	2.11	10.31	46.33	0.15	0.42	1.58	16.34	0.70	0.17	6.22	0.07	0.08
29	1.97	2.33	11.00	47.82	0.16	0.26	1.89	14.05	0.71	0.15	6.73	0.12	0.08
30	1.45	2.11	9.70	43.25	0.13	0.66	1.73	15.45	0.74	0.17	6.88	0.11	0.08

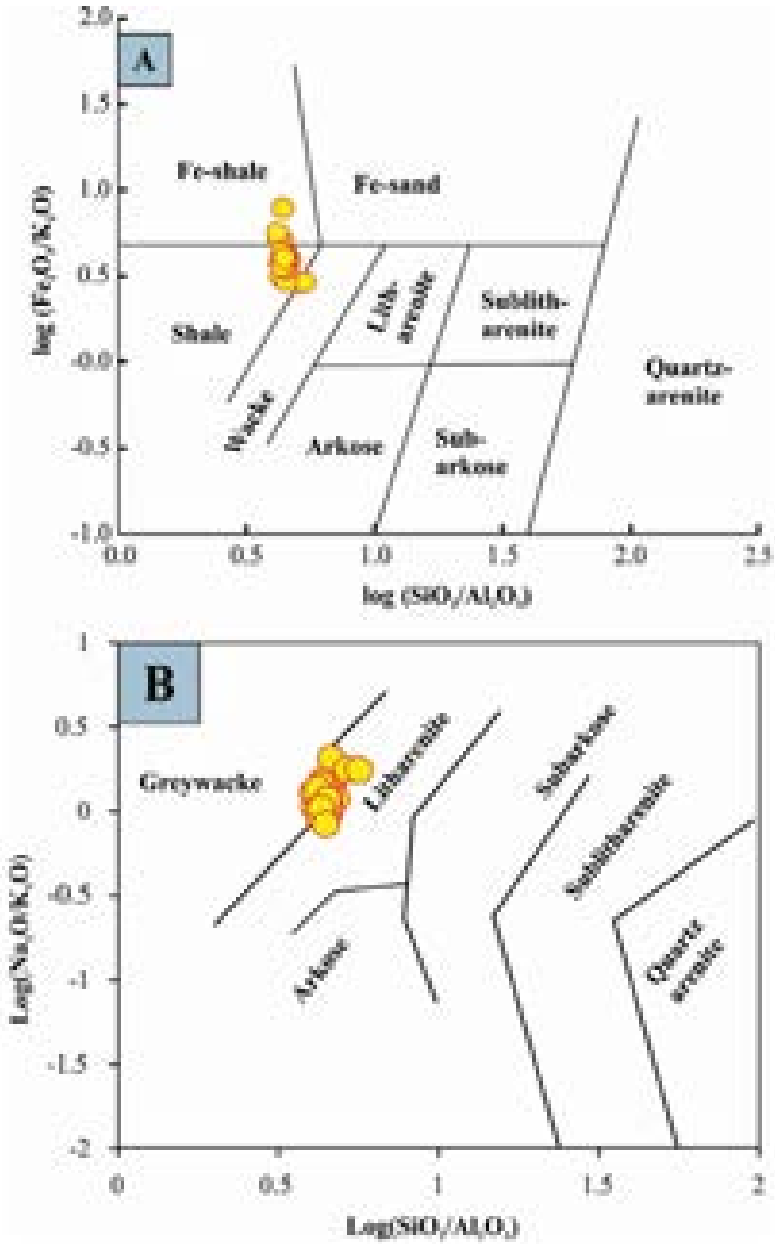


Fig. 6. Geochemical classification of samples using A) $\log(Fe_2O_3/K_2O)$ vs. $\log(SiO_2/Al_2O_3)$ and B) $\log(Na_2O/K_2O)$ vs. $\log(SiO_2/Al_2O_3)$ diagrams [29]

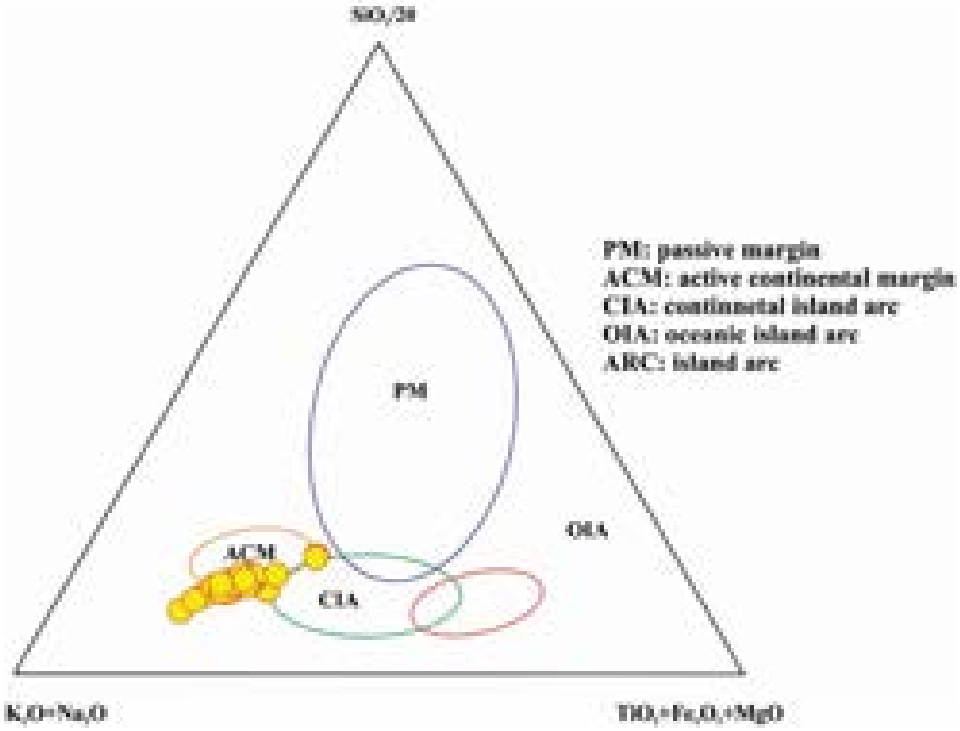


Fig. 7. Discriminant diagram for the tectonic setting of the samples [after 20]

the dominance of terrigenous components and a relatively low mineralogical maturity [29]. However, the significantly high calcite content in the mineralogical composition (Table 2) also points to a mixed carbonate-terrigenous origin for the sediment.

The ternary diagram provided in Fig. 7, which utilizes major element concentrations to infer the tectonic setting in which the oil-saturated rocks were deposited, shows the majority of the samples clustering predominantly within the active continental margin field, with only a minor scatter or inclination towards the adjacent continental island arc field. This strong localization indicates that the source materials were overwhelmingly derived from a convergent margin setting, typical of regions where continental crust is being actively consumed or uplifted, implying tectonic instability and rapid erosion, which is consistent with the generally immature nature observed in the Fig. 6B.

The clustering of the Beridash samples, along with the DF1 and DF2 data points (Fig. 8), within the defined provenance fields indicates a complex sediment source. The primary presence within the intermediate igneous provenance field suggests a

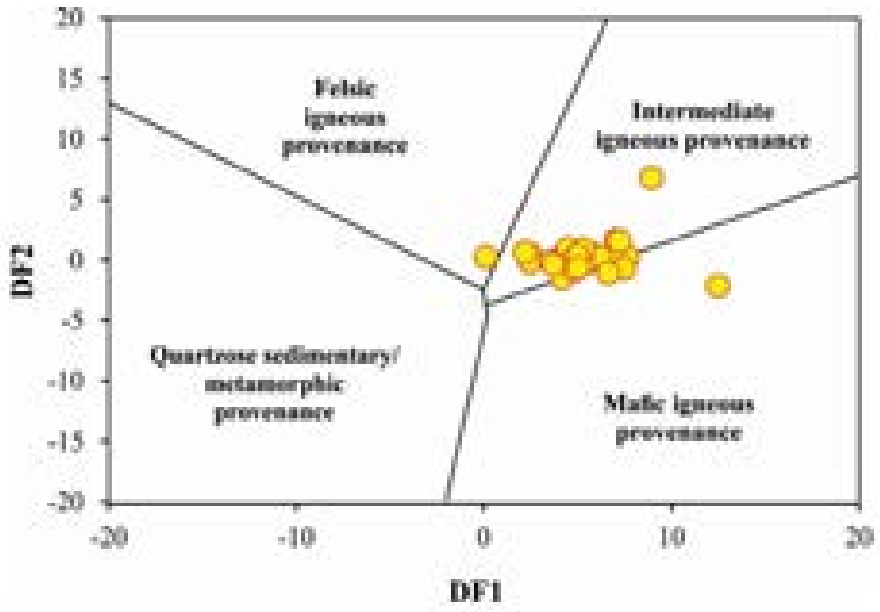


Fig. 8. Classification plot of discriminant functions DF1 and DF2 for the studied samples. Provenance fields are from [42]

dominant contribution from rocks like andesites or diorites. However, the proximity or mixing with the felsic igneous and mafic igneous provenance fields points to an additional, mixed source component. This implies that the sediments were not derived from a single, uniform rock type but from a terrane where both silicic and more basic igneous rocks were being eroded, **a setting consistent with the dynamic tectonic environment of an active continental margin.**

Oil abundance

In addition to geological parameters, the economic potential of oil-bearing sandstones is largely determined by their hydrocarbon composition and physico-chemical properties. Specifically, along with factors such as burial depth, thickness, and mineralogical composition, the amount of hydrocarbons contained within these rocks serves as a key indicator of their suitability for industrial exploitation. Studies have shown that the presence of approximately 6% hydrocarbon compounds in the rock composition indicates economically viable conditions for utilization [33].

The oil content in the analyzed samples ranges from 3.74% to 11.94% (Table 4), with an average value of 7.64%, which is considered to be of commercial significance [33]. Analysis of the spatial distribution of oil saturation across the study area (Fig. 9) reveals a progressive increase in oil impregnation from the northwest toward the southeast.

Moisture

Based on the mineralogical classification presented in Figure 5, the positioning of the oil-bearing rock samples within the ductile-brittle transition zone indicates that they contain both clay minerals and a relatively high proportion of carbonates, primarily calcite. Such a mineralogical composition exerts dual effects on the mechanical behavior of the rocks. Expanding clay minerals, such as montmorillonite, can block pore spaces, thereby reducing porosity and permeability. In wet conditions, the pores of montmorillonite expand due to water molecules, restricting the movement of the liquid phase, which negatively impacts oil saturation [23; 31]. This process is also strongly dependent on pore size, as micropores are easily blocked by adsorbed water [19].

Conversely, a significant concentration of quartz (mean 23.57%) together with the predominance of the calcite phase (mean 24.97%) induces notable changes in the physical properties of the rocks, including fragmentation, creating favorable conditions for the retention and storage of hydrocarbons [24: 35; 38; 47].

Table 4

Moisture and oil content characteristics of the samples

Sample	Moisture. %	Oil content. %
1	1.06	6.37
2	1.19	6.07
3	1.16	6.96
4	1.32	10.24
5	0.92	5.37
6	1.29	9.67
7	1.40	9.23
8	0.93	8.63
9	1.30	7.99
10	1.37	9.64
11	1.32	5.51
12	0.92	8.83
13	1.36	6.02
14	1.01	8.05
15	1.30	9.72
16	1.13	7.14
17	1.21	7.52
18	0.85	7.36
19	1.16	10.28
20	0.88	8.77
21	1.43	6.25
22	0.93	9.86
23	1.34	6.53
24	1.00	11.94
25	1.12	5.87
26	1.10	5.12
27	1.00	3.74
28	1.19	7.66
29	0.93	6.81
30	1.16	6.12
Average value	1.14	7.64

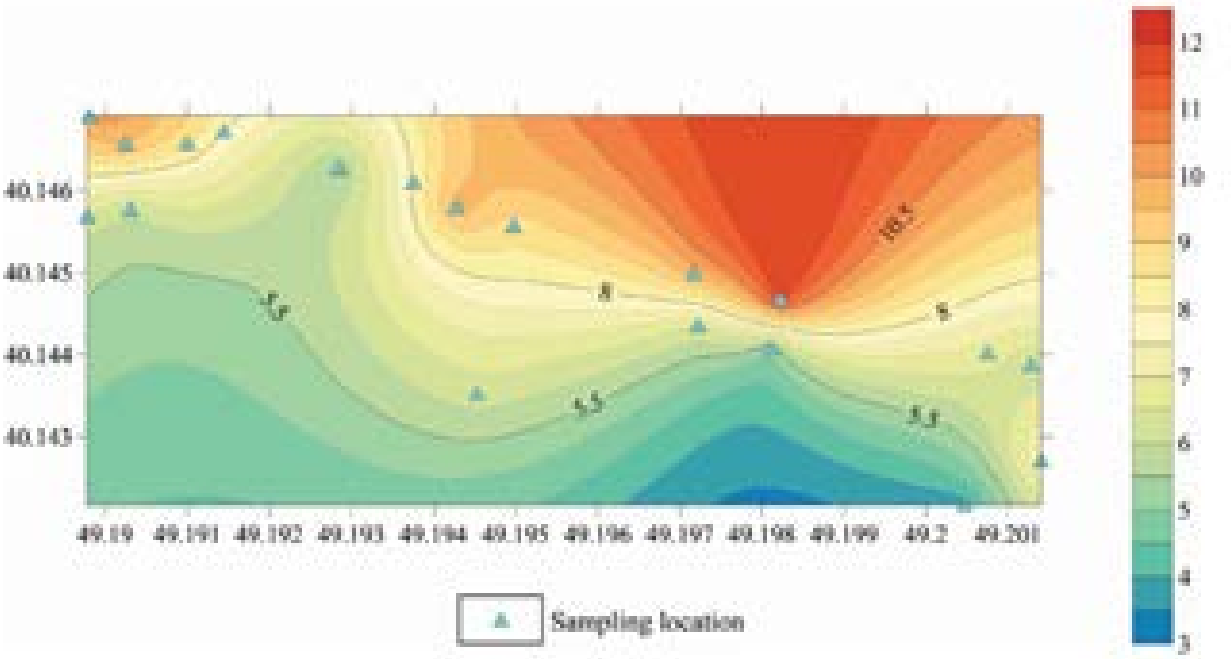


Fig. 9. Spatial distribution map of oil content concentrations in the oil-bearing rocks of the Beridash area

Furthermore, the weak correlation (r = 0.02) between moisture content (0.85%-1.43%) and oil enrichment indicates that moisture is not a primary factor influencing oil saturation. Instead, mineralogical composition, particularly the ratio of montmorillonite to calcite, plays a decisively dominant role (Fig. 10). This finding is also consistent with the spatial distribution of moisture across the study area (Fig. 11). A detailed analysis of the spatial distribution models (Fig. 9 and Fig. 11) further confirms the direct genetic link between the local lithological framework and fluid productivity. Across the mapped sequence, a distinct lateral mineralogical variation is observed along the strike of the beds. In the northwestern sector of the Beridash outcrop (see Fig. 1; e.g., Samples 7, 9, 10), the rock matrix exhibits an increase in ductile clay minerals (up to 25% in Sample 9). This specific lithological composition promotes elevated moisture retention (1.30-1.40%) and restricts maximum hydrocarbon accumulation due to pore-blocking. Conversely, a lateral facies shift occurs towards the central and southeastern sectors (e.g., Samples 19, 22, 24), where the mineralogical composition becomes heavily dominated by brittle components, specifically quartz and calcite. This southeastern zone corresponds precisely with

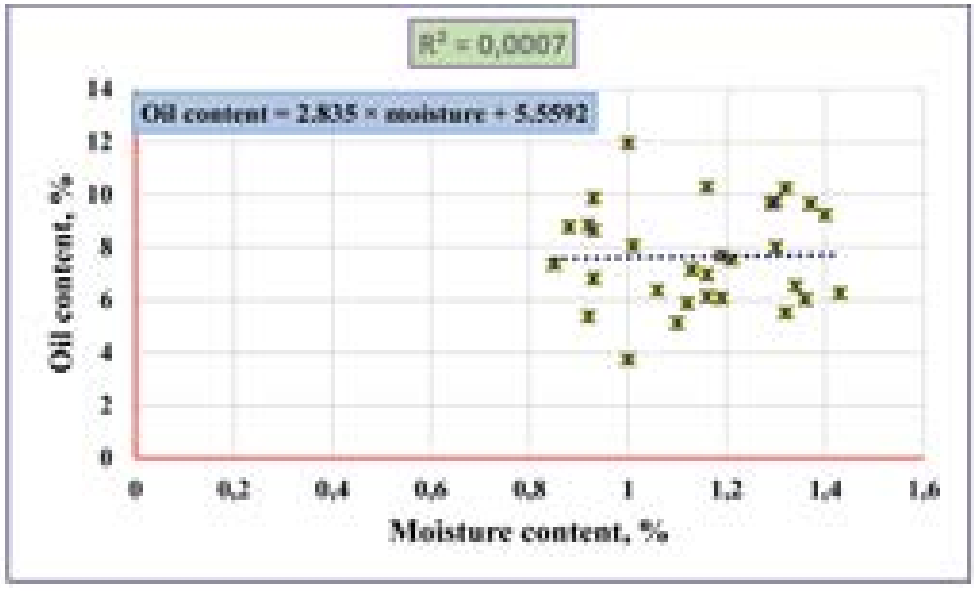


Fig. 10. Correlation diagram showing the relationship between oil content and moisture in the samples

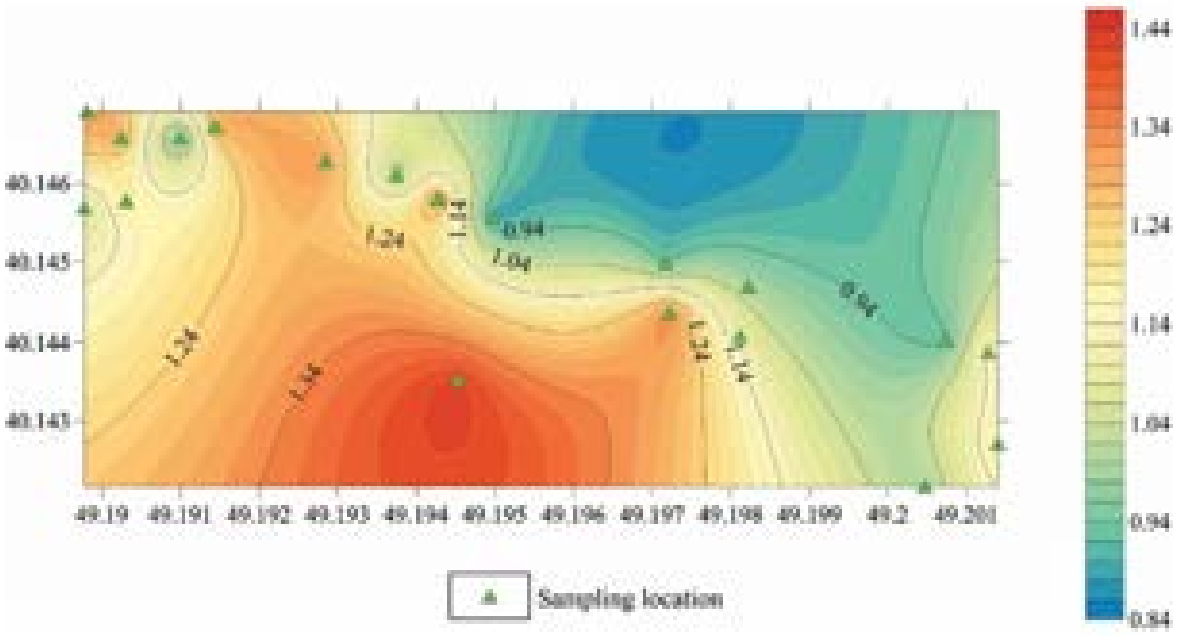


Fig. 11. Spatial distribution map of moisture across the study area

the areas of minimum moisture content (0.88-1.00%) and maximum oil impregnation, reaching peak values of 10.28% (Sample 19) and 11.94% (Sample 24). Finally, towards the far southern and southeastern boundaries (e.g., Samples 21, 27), the depletion of calcite (dropping to 21%) alongside high moisture (up to 1.43% in Sample 21) leads to minimum oil contents (3.74-6.25%). Thus, the spatial productivity is strictly controlled by the lateral variation in the rock's fundamental mineralogical composition.

Conclusions

The integrated formational analysis of the extensively exposed lower Pliocene Productive Series in the Beridash field establishes its substantial potential as a non-conventional hydrocarbon resource. Field mapping confidently delineated eight massive, predominantly calcareous sand and sandstone units localized within the 1245-1480 m interval from the top of the Lower PS.

Geochemical and mineralogical proxies demonstrate that these mixed carbonate-terrigenous sediments were deposited in a shallow marine-lagoonal setting along an active continental margin, originating from moderately weathered felsic and mafic sources.

The studied strata exhibit robust commercial potential, with oil saturation averaging 7.64% and reaching peak accumulations of 11.94% in the southeastern sector. The data establishes a near-zero correlation between background moisture and oil enrichment. Instead, lateral productivity is strictly dictated by the internal rock matrix: zones dominated by brittle components (where calcite and quartz reach up to 52%) provide an optimal framework for peak oil storage. Conversely, a lateral increase in ductile, swelling clays (e.g., montmorillonite) towards the northwestern sector physically impedes hydrocarbon accumulation. These findings offer a robust predictive evaluation model for exploring similar regional unconventional outcrops.

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Внесок авторів: всі автори зробили рівний внесок у цю роботу
Конфлікт інтересів: автори повідомляють про відсутність конфлікту інтересів
Декларація про використання генеративного штучного інтелекту: автори підтверджують, що під час підготовки рукопису не використовувалися інструменти штучного інтелекту.

Authors Contribution: All authors have contributed equally to this work.
Conflict of Interest: The authors declare no conflict of interest.

Declaration of use of generative artificial intelligence: The authors confirm that no AI tools were used during the preparation of the manuscript.

Походження та нафтоносний потенціал нафтоносних порід у родовищі Берідаш (Південний Гобустан, Азербайджан): мінералого-геохімічна оцінка

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АНОТАЦІЯ

У цьому дослідженні представлено комплексний формаційний аналіз широко розкритих нетрадиційних порід-колекторів нижнього пліоцену продуктивної серії (PS) на родовищі Берідаш (Південний Гобустан, Азербайджан). Використовуючи літологічні, мінералогічні та геохімічні показники, дослідження оцінює їхнє осадове середовище, походження та нафтовий потенціал, наголошуючи на мінералогічному контролі накопичення вуглеводнів. Незважаючи на великий видобуток традиційних вуглеводнів в Азербайджані, нетрадиційні нафтоносні поверхні залишаються геологічно недостатньо дослідженими. Це дослідження має на меті окреслити походження та вуглеводневий потенціал родовища Берідаш за допомогою інтегрованої мінералогічної та геохімічної оцінки, з особливим акцентом на механізмах контролю збагачення нафти. Аналітична методологія інтегрувала детальне картування поверхні, мінералогічні характеристики за допомогою рентгенівської дифракції (XRD) і геохімічну оцінку основних оксидів за допомогою рентгенівської флуоресценції (XRF) та ICP-MS. Вміст олії розраховували гравіметрично після поправки на вологість. Детальне картографування поверхні виявило вісім окремих, переважно вапняних нафтоносних піщаних і піскових одиниць, локалізованих у стратиграфічному інтервалі 1245-1480 м від вершини Нижнього ПС. Мінералогічно породи являють собою змішану карбонатно-теригенну товщу, в якій переважають кальцит (середнє 24,97%) і кварц (середнє 23,57%), а також глинисті мінерали. Геохімічні проксі вказують на відкладення в мілководному морсько-лагунному середовищі вздовж активної континентальної окраїни зі змішаних кислих і мафічних джерел. Середній вміст нафти становить 7,64%, зростаючи з північного заходу на південний схід. Слабка кореляція (r = 0,02) між вологістю (в середньому 1,14%) і нафтонасиченням демонструє, що мінералогія, зокрема співвідношення флюїдоблокуючих глин і крихких мінералів, діє як основний контроль накопичення вуглеводнів. На основі детального картографування поверхні вісім окреслених блоків вапняного піску та пісковика представляють собою дуже перспективний нетрадиційний ресурс вуглеводнів. Їх специфічне походження створило мінералогічний каркас, який дуже сприятливий для розміщення вуглеводнів, функціонуючи в основному незалежно від впливу вологи. Ці висновки забезпечують надійну формувальну модель оцінки регіональних нетрадиційних ресурсів.

ІНФОРМАЦІЯ ПРО СТАТТЮ:

Рукопис надійшов
24 жовтня 2025

Отримано після рецензування
4 квітня 2026

Затверджено до друку
25 травня 2026

Опубліковано онлайн
30 травня 2026

Ключові слова:

Азербайджан, продуктивна серія, нафтоносні породи, мінералогія, геохімія, походження, збагачення нафти, вологість, нафтоносність.

https://doi.org/10.26565/2410-7360-2026-64-04

УДК 551.243

Реконструкція незбалансованого розрізу Флішових Карпат

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АНОТАЦІЯ

Представлено результати експериментальних досліджень в сфері чисельного відновлення деформаційної історії складчасто-насувних орогенів без внесення будь-яких суттєвих змін у вихідний геологічний розріз чи схему будови, що в першу чергу стосується складчастості. Комплекс досліджень базується на застосуванні найбільш загальних, концептуально нейтральних механізмів формування складчастих структур, а саме: вигину і неспіввісної течії. Повна реконструкція розрізу Флішових Карпат в межах українського сектору виконана для центрального перетину Кросненської і частини Скибової зон за допомогою послідовного зняття зазначених деформацій, а також компенсації насувних переміщень, в результаті отримана величина загального 4-кратнього орогенного горизонтального скорочення та відновлені деякі риси вихідного басейнового профілю. Не виявляє протиріч порівняння отриманих кількісних результатів з даними попередніх досліджень методом збалансованих розрізів.

У контексті рішення прямої задачі реконструкції розрізу, представленого різноманітною складчастістю, розвивається підхід, що ставить поводження шаруватого розрізу що деформується в залежність від характеру навантаження (дії зовнішніх чи масових сил), умов на границях і властивостей самого розрізу, останнім виявляється зв'язок виникаючих структур з особливостями седиментаційного етапу розвитку басейну. Розломні зсуви вводилися штучно як незалежні складові загального процесу в'язкопластичного деформування. Методом кінцевих елементів виконана серія чисельних експериментів по відтворенню типових для складчастих орогенів асиметричних флексурних складок, складчасто-насувних парагенезисів, а також симетричних складок, обумовлених горизонтальним стисканням чохла. Показано, що для їхнього формування необхідна присутність компетентного шару і заданих умов ковзання в підошві шаруватої товщі; для виникнення симетричних складок важливим є варіювання міцності компетентного шару уздовж розрізу. Чисельне моделювання на етапі рішення прямої задачі надає повний спектр характеристик деформаційного процесу: кутів нахилу і величин головних напруг, величин деформацій стиску і зрушення, і т.п., що дозволяє проводити ефективне порівняння експериментальних висновків з даними вивчення природних об'єктів. На основі отриманих моделей складкоутворення як приклад проведено відновлення процесу формування типового для центрального перетину Українських Карпат складчасто-насувного розрізу Кросненської зони.

ІНФОРМАЦІЯ ПРО СТАТТЮ :

Рукопис надійшов
11 листопада 2025

Отримано після рецензування
14 травня 2026

Затверджено до друку
25 травня 2026

Опубліковано онлайн
30 травня 2026

Ключові слова:

складчасті пояси, палінспастична реконструкциія, незбалансований розріз, складчасто-насувні деформації, вигин, неспіввісна течія, чисельне моделювання, напружений стан, Флішові Карпати.

Вступ

Стаття є завершальною в циклі робіт, присвячених кількісному тектонофізичному дослідженню процесів, що обумовили розвиток різних регіонів України у фанерозої: Гірського Криму, западин Чорноморського басейну, ДДЗ та Донбасу [1-3 та ін.]; в кожній з них присутні окремі специфічні аспекти геологічного застосування кількісних побудов. У випадку Карпат ключовим напрямком таких досліджень повинно, звичайно, бути відтворення типової геосинклінальної складчастості та складчасто-насувного парагенезису, яки неможливо відокремити від контексту більш широкого кола проблем регіональної геодинаміки, палеобасейнової та орогенічної.

Реконструкція і моделювання структури складчасто-насувних орогенів є традиційно найбільш складною і суперечливою сферою в геотектоніці, де основна проблематика пов'язана з питаннями вивчення і трактування різ-

Як цитувати : Гончар Віктор (2026). Реконструкція незбалансованого розрізу Флішових Карпат. *Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology*, (64), 49–60. https://doi.org/10.26565/2410-7360-2026-64-04

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номанітних деформаційних процесів у зв'язку з існуючими геодинамічними моделями. Регіон Флішових Карпат надає один із прикладів такого тривалого і дискусійного дослідження, у поглядах на розвиток якого завжди існували і продовжують зберігатися як принципові розходження, так і розбіжності в близьких трактуваннях [4-13 та ін.]. Останні два десятиріччя відзначені широким впровадженням методів чисельного аналізу у вивчення тектонічного розвитку Карпат, у першу чергу – реконструкцій на основі т.зв. методу збалансованих розрізів, чим відкриваються нові можливості інтерпретації тектонічного і зв'язаних з ним процесів, моделювання і виведення результатів у контекст більш масштабних палеотектонічних побудов, але теоретична і методична основа таких побудов залишається вузькою, обмеженою рамками механізму насувно-лускового (рампового) деформування осадового чохла у наслідок акреції [14-19]. Як результат, на збалансованих профілях відсутні складки, що позбавляє їхнього застосування у відношенні традиційних напрямків структурно-тектонофізічного аналізу, а також в дослідженні та прогнозі родовищ нафти і газу, зокрема у Передкарпатському прогині, де основна частина скупчень вуглеводнів пов'язана саме зі складчастими структурами [20].

До особливостей методики реконструкції розрізу і відновлення процесу складкоутворення. Незбалансований розріз можна визначити як синонім складчастого; це тим більше вірно, чим детальніше масштаб розгляду структури. Не можна заперечувати значення насування, і наступного за ним формування скиб при становленні складчастих поясів, а отже – надсубдукційного акреційного механізму деформування чохла [15, 18], але коли збережена навіть на збалансованих розрізах складчастість не відтворюється потім прямим моделюванням (рис. 1, А), випливає можливість говорити про прояв інших механізмів басейнової інверсії й орогенезу, як загальне колізійне стискання літосфери або гравітаційний тектогенез. У межах Флішових Карпат найбільш яскравими прикладами такого *складчастого опору* є структури Сілезької і Кросненської зон, тилові частини Скибової, міоцен Самбірській зони (рис. 1, Б і В) та інши, що містять симетричні антикліналі і синкліналі, вергентні асиметричні складки з розвинутими замками і підвернеными крилами, складки з протилежною вергентністю. Окрим того, не виводиться з концепції акреційного тектогенезу (де використовується механізм вигину плити, що занурюється) крутий уступ фундаменту, що формує приплатформний борт Передкарпатського крайового прогину. У якому ступені ці (та інші) структури можуть скорегувати вже отримані результати реконструкцій і, далі, яку інформацію можуть вони нести щодо більш загальних висновків і геодинамічних побудов? Щоб відповісти на ці питання, варто застосувати методи реконструкцій і моделювання, для яких розмаїття складчастих форм не є проблемою.

Врахування закономірностей природнього складкоутворення. У межах досить простих наближень у рамках чисельного моделювання деформацій шаруватої осадової товщі можна одержати цілком ясні відповіді на питання про основні закономірності, що керують процесом складкоутворення. Але відштовхуватися в них потрібно від ключових фактів природнього походження. У відслоненнях передових частин складчастих поясів можна побачити свідчення того, що типова для них вергентна складчастість розвивається поза залежністю від проростання базального розлому-детачмента нагору і насування, виявляючи собою скоріше результат виклинцьовування маловязкой осадової товщі в основі розрізу (блокування базального ковзання). Вищі шари, при цьому, випробуючи бічний стиск мнуться в складки (результат подовжно-поперечного вигину [24]), форма яких залежить у першу чергу від особливостей літофаціального складу: присутності чи відсутності компетентного шару, характеру розподілу міцності, пролонгації зриву в підошві, а також, зрозуміло, появі і розвитку розломів. Тому припускаємо (у рамках механіки суцільного середовища), що розломи, як і складки, виникають на визначених етапах деформаційного процесу унаслідок виконання реологічних законів в'язкопластичної течії, і їх варто розглядати в генетичному контексті як незалежні агенти такої (тектонічної) течії [25].

Методика реконструкції

Використована техніка реконструкції, тобто, повернення складчастого розрізу у вихідний недеформований стан полягає в послідовному застосуванні (після оцифровки) процедур зняття деформації загальної неспіввісної течії і, потім, випрямлення шарів (зняття вигинної складової). До перших побудов цього типу відносяться роботи [24, 23], де можна знайти формальний опис чисельних процедур на різноманітних прикладах карпатських складок. Деякі специфічні технічні питання, пов'язані з адаптацією безперервного складчасто-насувного розрізу, включаючи урахування розломних зсувів, пояснюються безпосередньо на конкретних прикладах в тексті і на рисунках. Основне методичне спрощення полягали в прийнятті постійних загальних для розрізу величин, що визначають етап горизонтальної неспіввісної

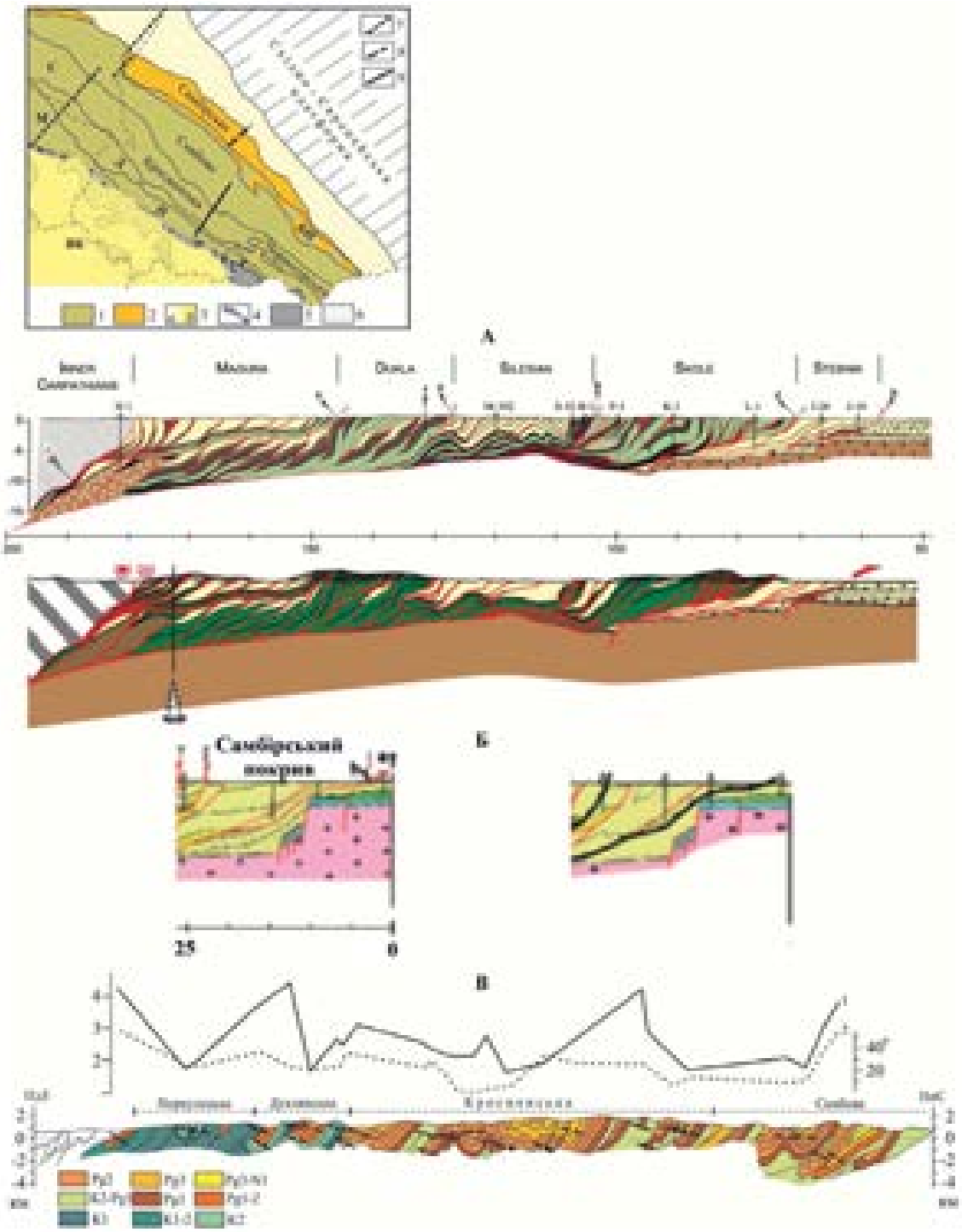


Рис. 1. Розрізи Флішових Карпат: А – збалансований профіль (угорі) та відповідний йому модельний (за [15]); Б – збалансований (ліворуч) та вихідний геологічний профілі Самбірської зони (за [17]); В – геологічний розріз за матеріалами зйомки м-бу 1:200 000 [21, 22], що містить дані щодо умов деформування, отримані на основі аналізу складчастості: угорі криві встановлених по складкам величин кратного осьового стискання (1), кута зсування (2) за умов горизонтальної неспіввісної деформації; парами стрілок на розрізі показані реконструйовані орієнтування головних стискаючих напружень (за [23]).

Угорі на урізанні показано схему будівлі Східних Карпат; структурно-фаціальні зони: М – Магурська, С – Сілезська, Д – Дуклянська, П – Поркулецька, Р – Рахівська, БП – Бориславсько-Покутська; ВК – Внутрішні Карпати. 1 – Флішові Карпати. 2 – внутрішні деформовані зони Передкарпатського прогину, 3 – недеформований чохол відклади Передкарпатського прогину (а) та Внутрішніх Карпат (б), 4 – Утьосові зони, 5 – Мармароський метаморфічний масив, 6 – вулканічні породи; положення профілів: 7 – [15], 8 – [17] , 9 – [21, 22].

Fig. 1. Flysch Carpathians cross-sections: A – balanced (above) and its model (after [15]); Б – balanced (left) and initial geological profiles of Sambir zone (after [17]); B – geologycal profil scale 1:200 000, which contains initial data on deformation conditions, which received on a basis of folds: above – curves of sizes of axial shortening (1), shear corner (2) in conditions of noncoaxial deformation; pairs of arrows on a cross-section the orientations of the main compressing stresses (after [23]).

Above on insert the scheme of a tectonic structure of the East Carpathians is shown; basic structural-facial zones: M – Magura, C – Silesian, Д – Ducla, П – Porkuletska, P – Rakhivska, БП – Borislav-Pokutska; ВК – Inner Carpathians. 1 – Flysch Carpathians, 2 – deformed inner zones of Carpathians foredeep, 3 – undeformed cover of Carpathians foredeep (a) and Inner Carpathians (б), 4 – Clippen belts, 5 – Marmarosh metamorphic massiv; 6 – volcanic rocks; profiles distribution: 7 – [15], 8 – [17] , 9 – [21,22].

течії – однорідності деформації з постійним кутом нахилу осі стиску. Більш детальні процедури, пов'язані з урахуванням нерівномірного деформування, потребують лише більш кропіткого програмування. Раніше, для загальних регіональних побудов використовувався скорочений варіант експрес-реконструкції і моделювання на основі теорії неспіввісної течії [26,10], в якому враховується і, відповідно, знімається лише складова в'язкопластичної течії, яка вбирає левову частку загального деформування [23], однак без врахування об'ємної складової.

Рішення прямої задачі реконструкції засновано на чисельному моделюванні методом кінцевих елементів процесу складкоутворення в осадовому чохлі. Розвивається апробований раніше підхід, що ставить поводження слоїстого розрізу що деформується в залежність від характеру навантаження (дії зовнішніх чи масових сил), умов на границях і властивостей самого розрізу; останнім виявляється зв'язок виникаючих структур з особливостями седиментаційного етапу розвитку басейну [27]. Чисельне моделювання на етапі рішення прямої задачі надає повний спектр характеристик: кутів нахиу і величин головних напруг, величин деформацій стиску і зрушення, і т.п., що дозволяє проводити ефективне порівняння експериментальних висновків з даними вивчення природних об'єктів. Розломи вводяться штучно на певному етапі деформування як вузькі зоні з аномально низким опором; отриманий таким чином складчасто-насувний парагенезіс відповідає природним формам, що і доводиться нижче.

Реконструкція профілю Кросненської і Скибової зон по лінії Хуст – Івано-Франківськ

Вихідний профіль характеризує будівлю Флішових Карпат у центральному перетині українського сектора, включаючи цілком Кросненську зону і половину, що примикає до неї, Скибової (рис. 2, А). Він відноситься до верхнього масштабного рівня, що поки не охоплений технікою збалансованих розрізів, тобто, він більш детальний і добре демонструє той факт, що Флішові Карпати – складчасті. Пропонована повна реконструкція означає, що будуть зняті всі складчасто-насувні деформації, властиві флішовому комплексу, включаючи деформації при скороченні кори басейнів на передорогенній стадії, коли відбувався первинний стиск чохла з оформленням основного складчасто-насувного парагенезісу.

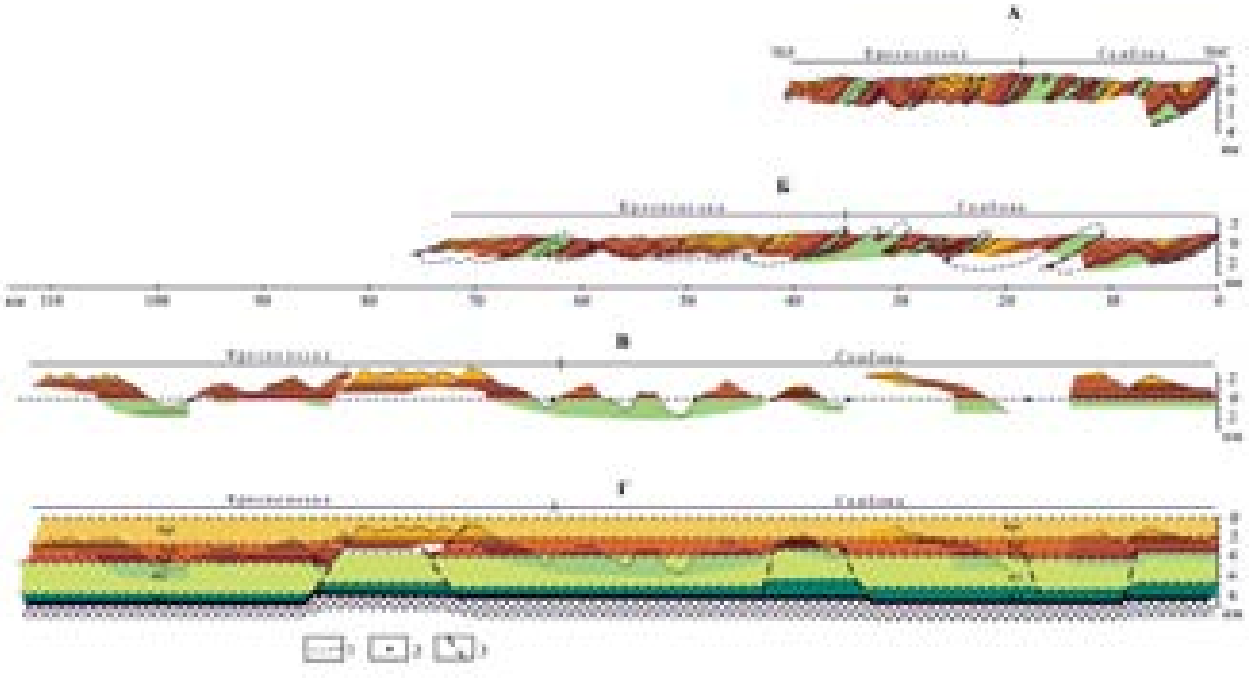


Рис. 2. Реконструкція розрізу Кросненської і Скибової зон у центральному перетині Українських Карпат (фрагмент профілю, показаного на рис. 1, В).
А – вихідний стан; Б – після зняття деформації однорідної горизонтальної неспіввісної течії; В – результат випрямлення шарів; Г – повна реконструкція басейнового розрізу з вирівнюванням щодо покрівлі олігоцену, з обліком регіональної стратиграфічної схеми. 1 – базова границя вирівнювання/проекції розрізу, що випрямляється; 2 – крапки з'єднань базової границі, розірваної насуванням; 3 – прогнозовані скидання в реконструйованому басейновому розрізі.

Fig. 2. Reconstruction of cross-section of Krosno and Skiba zones in central part of Ukrainian Flysch Carpathians (fragment of profile, showed on fig. 1, B).
A – initial condition; Б – after removal of deformation of uniform horizontal uncoaxial flow; B – result of straightening of layers; Г – full reconstruction of basin profile with alignment relatively the top of Oligocene, taking into account of regional stratigraphic scheme.
1– base boundary of straightening /projection of unbended profile; 2 – points of connection of base boundary, breaked by faults; 3 – normal faults, which have prognosed within reconstructed basin profile.

Задача першого етапу реконструкції з застосуванням теорії неспіввісної течії – це приведення розрізу в стан з рівним розподілом потужностей на крилах і в замках складок, щоб далі застосувати процедуру випрямлення шарів. Для цього, у прийнятому тут спрощеному варіанті реконструкції необхідно підібрати таку загальну (середню) деформаційну обстановку, при якій складки всього розглянутого розрізу в максимальному ступені задовольняли б даній вимозі. Знайденою такою обстановкою виявилося неспіввісне деформування при суттєво положистому нахилі осі стиску 5° і величині деформування $d = 0.63$ (кратна 1.6) горизонтального стиску. Результат такої реконструкції, зрозуміло, є неідеальний у плані вирівнювання всіх потужностей (рис. 2, Б), але цілком придатний для виконання наступних кроків.

Отриманий проміжний розріз далі піддається деякої реставрації: у нього вноситься новий інтерпретаційний елемент – відновлюється безперервна стратиграфічна границя, спираючись на котру далі буде виконуватися випрямлення всього розрізу. Такою базовою лінією в нашому випадку (як найбільш збережена) може служити границя крейди/палеогену. Результат випрямлення всього розрізу і є формально повна палінспастична реконструкція (рис. 2, В). Отримано вихідну довжину 111.5 км, що в 2.75 рази перевищує кінцеву довжину розрізу (40.5 км). Ця оцінка практично збігається з реконструкцією, отриманою в попередній роботі [23]; вона, однак, не враховує ефекту стискальності середовища при деформуванні (див. нижче). Відзначимо для порівняння, що за даними [19] у свалявському перетинанні Карпат скорочення Кросненської зони складає 3.2 рази (93 і 29 км), для Скибової зони там же отримане скорочення в 2.77 рази (108 і 39 км).

Розріз має значні порожнечі внаслідок ерозії, зняття насувних переміщень, обмеженості вихідного варіанта по глибині. Також, він «незбалансований» по вертикалі, тому, на заключному етапі реконструкції було зроблено загальне вирівнювання реконструйованих фрагментів щодо покрівлі олігоцену, а також заповнення стратиграфічних зіянь по горизонталі і на глибину у відповідності зі стратиграфічною колонкою розглянутої ділянки Карпат [17]. У такий спосіб був отриманий остаточний варіант повної реконструкції вихідного геологічного розрізу (рис. 2, Г), при будові якого не постраждала жодна складка. Останнє означає, що в ході рішення прямої задачі реконструкції орогенічних рухів може бути встановлені зародження і простежене еволюція кожної складчастої структури вихідного розрізу.

Розріз ще може бути скорегований по довжині з урахуванням стискальності середовища з типовими для осадових порід величинами коефіцієнта Пуассона, що в середньому веде до збільшення вихідної довжини в 1.4 рази. Тоді одержуємо нову довжину відновленого басейнового профілю, що складе близько 165 км, що говорить вже про 4-кратне скорочення в ході орогенезу. Відзначимо для порівняння, що за даними [15] у західній частині Карпат для Сілезької зони кратність скорочення досягає 4.5 разів (93 і 24 км). У свалявському перетинанні за даними [19] скорочення Флішових Карпат склало 3.7 рази (328 і 89 км), що теж близько до нашої оцінки. У отриманому вигляді розріз вже має деяке відношення до басейнової реконструкції, характеризуючи серединний фрагмент древнього флішового трога, прилеглого до досить крутого континентального схилу Східно-Європейської плити [28]. Він містить отримані можливі западини і підняття фундаменту, а також скидові розломи, що є наслідком варіювання потужностей по простяганню. У цьому контексті інтерпретацію даних цікаво провести в порівнянні з реконструкцією аналогічної по будівлі ділянки Карпат, виконаної методом збалансованих розрізів. Таке порівняння дається на рис. 3, де вгорі показаний палеопрофіль Сілезької і Скибової зон з роботи [15]. Тому що в ній використовувався глибинний розріз Карпат з повним відображенням потужностей порід, на виході фігурують безперервно базальна частина палеобасейну і фундамент. Варіації потужності крейдових порід обумовили рельєф ложа, що складається із Сілезького піднятия і депресії, що відповідає Скибової зоні. Наш розріз, істотно обмежений даними по глибині, проте, демонструє якісно ту ж картину: підняття в межах основної частини зони Кросно і занурення в області Скибової; їхній масштаб щоправда менше, ніж на збалансованому розрізі, що випливає з прийнятого при трансляції профілю на глибину загальної потужності крейдової частини, тобто – з обмеження вихідних даних.

Чисельне моделювання складкоутворення и складчасто-насувного деформування. Стосовно Карпат вже з'являються дослідження, де в рамках палінспастичних реконструкцій методом збалансованих розрізів даються покрокові рішення прямої задачі, що показують хід розвитку акреційного орогена [15,19]. Формування орогена в них йде в кінематичному наближенні й у повній відповідності з моделлю насувно-лускатого деформування, де складчастість не відтворюється. У результаті виникає ситуація, коли на вихідному розрізі складки є, а на змодельованому, покликаному відобразити розвиток структур, їх немає [15, 17]. Наскільки велика така втрата в плані дійсної реконструкції орогеничного процесу, розкриття його закономірностей? Наприклад,

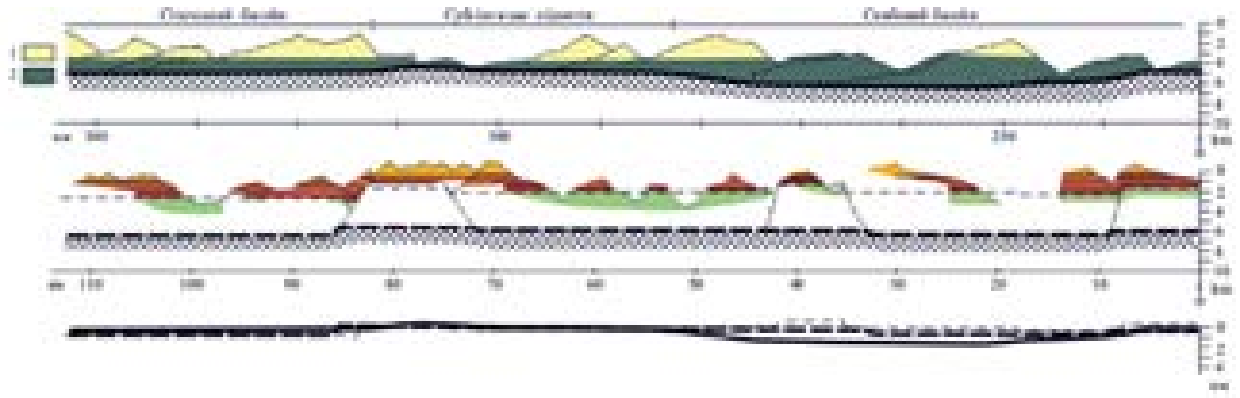


Рис. 3. Порівняння палінспастичних профілів Флішових Карпат, отриманих різними методами: угорі – збалансований розріз ([15] див. рис. 1, А, де 1 – палеогенові, 2 – крейда-палеоценові відкладення); нижче – цієї роботі; нижній графік демонструє співвідношення отриманих границь: фундаменту – товста, крейди/палеогену – тонка переривчаста лінія.

Fig. 3. Comparison of profiles of Flysch Carpathians odnained by different methods: above – ballansed cross-sections ([15], see fig. 1, A, 1 – Paleogene, 2 – Cretaceous-Paleocene); more low – this work; the bottom shows a parity(ratio) of the received borders: the basement – thick, Cretaceous/Paleogene – thin faltering line.

симетричні антикліналі Сілезської і Кросненської зон у формі гребеня (див. рис. 1, А і В), як показує моделювання аналогічних структур [27], можуть бути наслідком загального стиску чохла разом з фундаментом. Присутні в межах Кросненської зони складки зворотної (південно-західної) вергентності (рис. 1, В) можуть мати відношення до гравітаційного тектонічного потоку, що відчув деяку «завихореність» [29,25]. Обидва ці приклади дають привід для сумніву щодо одиничної дії акреційного механізму в процесі формування Карпат. Отже, побудови в області прямого моделювання повинні випереджатись, доповнюватись дослідженнями умов формування складчастих структур, що складають ороген. Нижче ця задача розглядається на основі чисельного моделювання, відповідно, складчастість відтворюється в рамках механіки суцільного середовища, одержувані результати ставляться у відповідність до діючих навантажень і міцностних властивостей розрізу (особливостям будівлі). Прийняте модельне пружнов'язкопластичне середовище описується типовими значеннями механічних параметрів для осадових порід (таблиця 1).

Розглядаються умови формування основної складчастості Флішових Карпат на макрорівні (в масштабі орогену) як реакція шаруватого середовища (осадового чохла) на зовнішнє бокове стискання. Можливим є також формування складчастості під дією масових сил – в парагенезисі із гравітаційними покривами або пов'язану з діапірами, а також вторинної складчастості в тонкошаруватих флішових товщах, в природломних зонах (волочіння), пошарової течії та ін., що має значення на мезо- та мікрорівнях структурних досліджень.

Перший приклад ілюструє відправну точку – просту флексуру, що формується над зоною блокування базального ковзання у відсутності компетентного шару (рис. 4, А). Складчастість тут практично не утворюється, вигин шарів у фронті формується внаслідок нерівномірного стовщення і підйому тилової частини. Уведення компетентного шару принципово змінює ситуацію (рис. 4, Б): унаслідок випереджального його вигину спостерігається становлення асиметричної антикліналі (флексурної складки – тобто складки, що поєднує риси флексури та складки вигину); відповідно відбувається перерозподіл деформації усередині товщі, базальний максимум якої витягається в напрямку перетинання короткого крила. Це ще не розлом, але така концентрація деформації може дати початок росту насування лістричного типу. У природі є приклади як реалізації даного розлому, так і розвитку асиметричної складки з підверненим крилом без нього. Тут важливим для нас є те, що саме складчастість виявляється родоначальною в складчасто-насувном парагенезисі, а не навпаки, тоді як в методології збалансованих розрізів саме разломні переміщення формують складку (див. рис. 3 в [14]). Траєкторії головних стискаючіх напруг пока-

Таблиця 1

Параметри, прийняті при моделюванні складчастості

Table 1

The parametres accepted at folds modelling

щільність, кг/м^3	2450
в'язкість (розлому, середи, компетентного шару), пуаз	$1\cdot10^{14}$, $1\cdot10^{18}$, $1\cdot10^{20}$
коэф. Пуасона	0.5, 0.15, 0.45
модуль Юнга, Па	$1\cdot10^{8}$, $5\cdot10^{8}$, $7{,}5\cdot10^{9}$
швідкість зміщення бок. стінки, м/рік	0.06 – 18

зують у цілому їх похилі в напрямку зсуву, від положистих (6 – 8°) до досить крутих (20 – 40°) у внутрішній зоні складки і поблизу підошви. Ці нахили в цілому відповідають реконструкціям положень головної осі стиску для карпатських складок [23,24] (див. рис. 1, В).

Нижче на рис. 4. Б показаний спільний розвиток складки і насуву, що був уведений штучно як вузька ослаблена зона, що перетинає коротке крило. Як видно, у цьому випадку у рух утягується простір нижче розглянутої товщі, тобто, – умовний ослаблений шар в підошві. Розвиток складчасто-насувних парагенезисів з виведенням траєкторій головних стискаючіх напруг відображене на рис. 4, В.

Наступний експеримент демонструє сформовану серію з трьох складок. Спочатку показаний результат послідовного зминання за рахунок дискретного просування детачмента (рис. 4, Г). Асиметрична антиклінальна складка займає фронтальне положення, більш ранні структури, що розташовані за нею, здобувають риси симетричних з максимумами деформацій уздовж вісей антикліналей, при цьому найбільшою стислістю характеризується саме тилова складка, що утворилася першої. Така послідовність може служити індикатором обстановки примусової акреції, тобто, саме тієї, котра розглядається в контексті субдукції плити. Зрозуміло, що класичний акреційний орогеn повинен, у принципі, володіти саме такою (зворотною) спрямованістю зростання ступеня стислості осадового чохла, поза залежністю від механізму деформування. Порушення цієї послідовності можна трактувати як опосередкована вказівка на присутність інших механізмів розвитку орогену, таких як загальний стиск літосфери чи реалізація гравітаційної нестійкості. На користь цього говорить завершальний експеримент (рис. 4, Д), де було застосовано вільне ковзання в підошві на всьому протязі товщі, який були додані випадкові варіації міцністних властивостей. Як видно, це призвело до утворення серії в загальному симетричних антикліналей довільного розміру і стислості.

Приклад рішення прямої задачі реконструкції для Флішових Карпат. Представлені вище й аналогічні їм моделі складкоутворення пропонується використовувати в прямій задачі реконструкції орогенічного процесу Флішових Карпат як прототипи структур геологічного розрізу, покликані показати ймовірний сценарій розвитку (проблему відтворення конкретних складчастих структур ми адресуємо майбутньому).

Пряме моделювання, слідом за палінспастічною реконструкцією, також доцільно розділити на два етапи: 1) різноманітного по механізмах, неоднорідного складчасто-насувного деформування первинного осадового розрізу, і 2) загальні рівномірні деформування в умовах горизонтальної неспіввісної течії. Вихідний розріз (рис. 5, внизу) відповідає відновленому за допомогою реконструкції профілю Кросненської і Скибової зон (див. рис. 2, Г), але скорегований по довжині з урахуванням стискальності, і в підсумку складає 166 км. Вибір модельних складок визначався так, щоб відтворити характерні риси Кросненської зони, що володіє специфічним набором симетричних складчастих структур, обрамлених більш типовими складчасто-насувними парагенезисами. Він має трохи занижену потужність стосовно реконструйованого палінспастичного профілю, що зроблено з урахуванням того стовщення, що здобувають шари в процесі деформування. Цей профіль складається із секцій, що відповідають моделям різних структур, процес розвитку яких відбудовується незалежно, тобто, профіль є штучно зкомбінованим. З початку, у ході першого етапу відбувається зародження флексурной антикліналі в першій секції, далі допускається випереджальний розвиток складчасто-насувного парагенезису у тилу і у фронті, між якими в умовах загального стиску формується складчастість з характерними рисами симетричних структур. Усе це призводить до результату, що завершує перший етап індивідуального розвитку усіх структур. На наступному, другому етапі до них прикладається єдина деформація горизонтальної неспіввісної течії, при який досягається необхідне 4-кратне підсумкове скорочення вихідного профілю.

Хоча масштаб отриманих структур трохи більший тих, що спостерігаються в приповерхніх розрізах, за формою і ступенем стислості модельні складки і складчасто-насувні тандеми цілком порівнянні з природними, що фігурують на розрізі Хуст – Івано-Франківськ (рис. 1, В), так що виконане моделювання дозволяє наочно уявити хід розвитку карпатської складчастості в серединному перетинанні; сам профіль може бути основою для подальшої більш детальної розробки.

Висновки

1. Для палінспастичної реконструкції складчастих поясів можуть бути використані геолого-структурні профілі у тім вигляді, у якому вони представлені авторами, без попередньої обробки балансуванням. Це відразу ставить проблему реконструкції звичайно присутньої на розрізах різноманітної за формою складчастості – найбільш інформативного індикатора у відношенні як власне деформацій, так і більш загальних умов тектогенезу. Запропонована програма реконструкції – антитезис

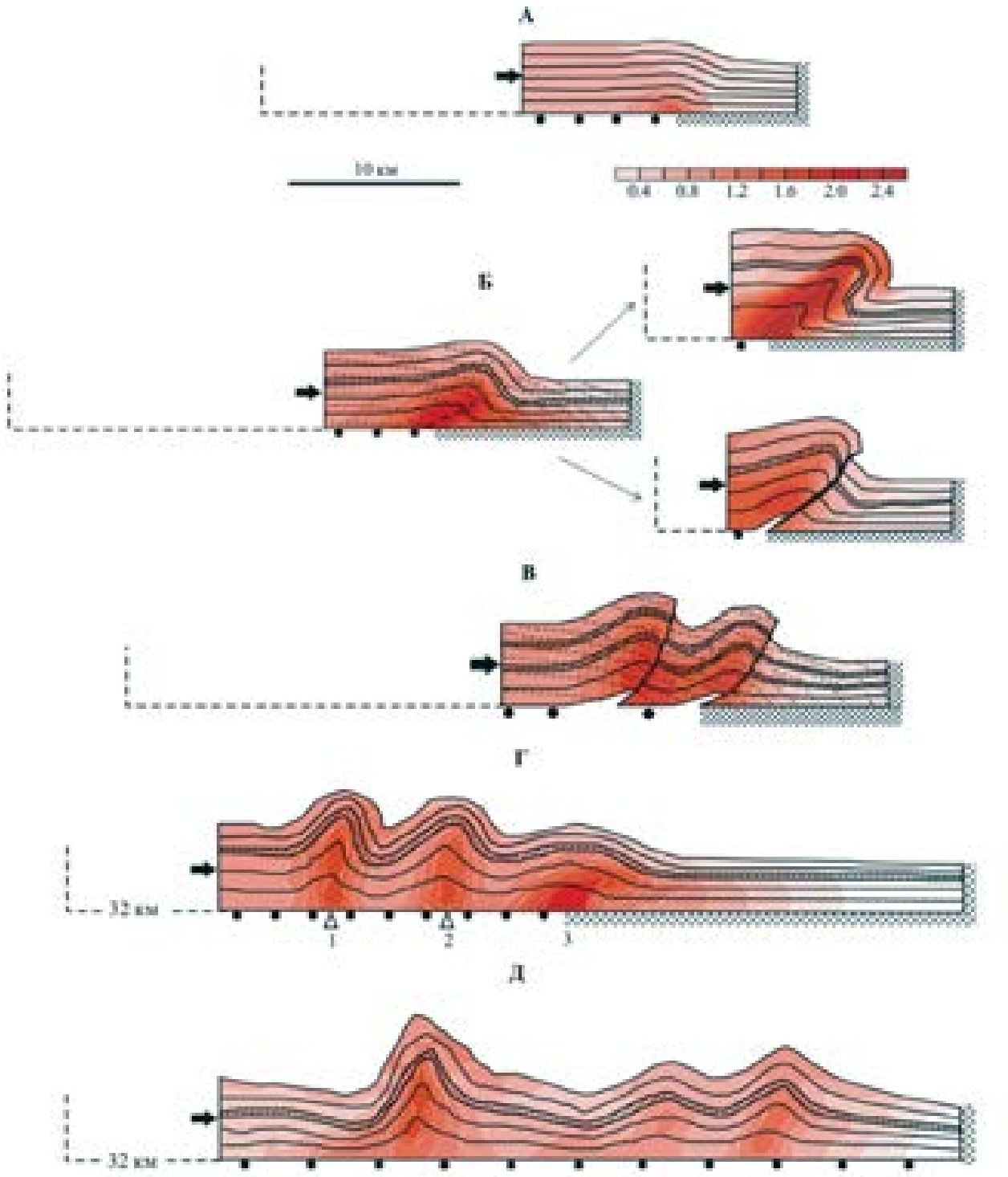


Рис. 4. Результати чисельного моделювання складчастості для цілей відтворення складчасто-насувного орогенезу.
А – проста флексура у відсутності компетентного слою (тонуванням показан розподіл еквівалентної деформації $\varepsilon_e = \sqrt{2/3}\sqrt{\varepsilon_x{}^2 + \varepsilon_{xy}^2 + \varepsilon_y{}^2}$); Б – флексурна складка, що поєднує риси флексури та складки вигину (заштрихований компетентний шар, тонкі переривчасті лінії – траєкторії максимальних стискаючіх напружень, товстою переривчастою лінією позначена вісь максимуму деформацій, як ймовірний напрямок зародження соскладчастого насування, що і реалізовано в моделі нижче); В – пари складчасто-насувного парагенезису; Г – розвиток складчастого ланцюжка внаслідок послідовного дискретного просуванні точки у підставі розрізу, що блокує (1, 2, 3); Д – вільний розвиток складчастості при варіаціях міцності компетентного шару.

Fig. 4. Results of numerical modelling of folding for purposes of reproduction of fold-thrust paragenesis.
А – simple flexure in absence of competent layer (isolines indicates values of aquivalent deformation $\varepsilon_e = \sqrt{2/3}\sqrt{\varepsilon_x{}^2 + \varepsilon_{xy}^2 + \varepsilon_y{}^2}$); Б – flexural fold (shaded the competent layer, thin discreet lines - trajectories of max compressional stresses, sick line indicates the axis of maximum of deformation as possible direction of generation of thrust, as is realizated in models below); В – the pair of fold-thrust paragenesis; Г – folds chain generation in result of consequent discrete advancement of blocking points in base of the section (points 1, 2, 3); Д – free development of folding in conditions of variations of durability of competent layer.

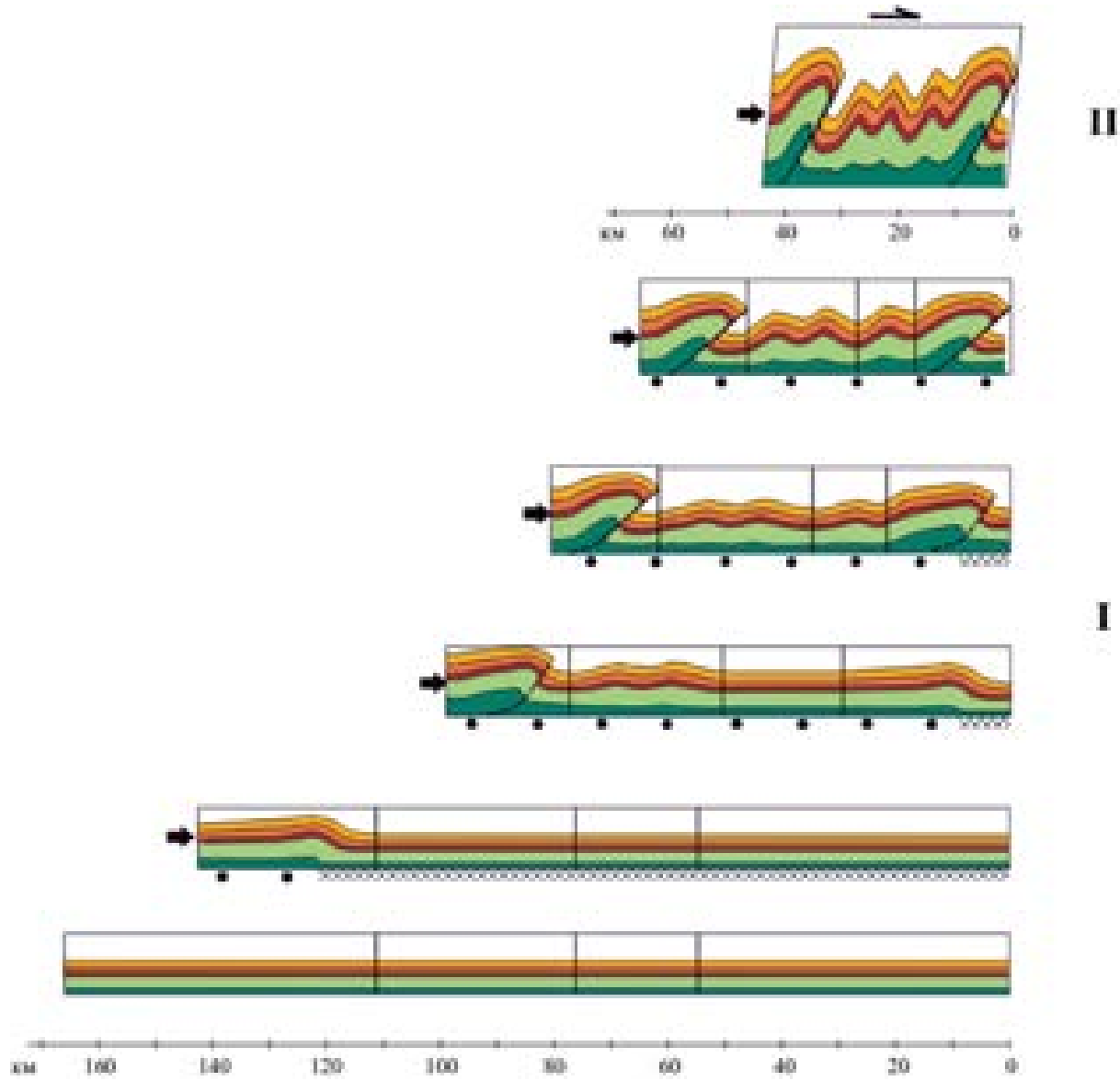


Рис. 5. Виконання прямої задачі реконструкції розрізу, типового для серединної частини Флішових Карпат (використані результати чисельного моделювання складчастих структур (див. рис. 4)).
Знизу нагору – стадії розвитку процесу в межах двох етапів: індивідуального розвитку структур (I) та загальної неспіввісної течії (II).
Див. пояснення в тексті.

Fig. 5. Direct problem decision of reconstruction of cross-section typical for middle part of Flysch Carpathians (results of numerical modelling on fig. 4 was used).
From bottom to up stages of development of process are shown: at stages of individual development of structures (I) and the general noncoaxial flow (II).

методології збалансованих розрізів, за яким може бути і синтез, вона сама по собі є спробою *збалансувати* сучасні структурно-тектоничні підходи.

2. В основу методики реконструкції складчастості покладено два нейтральних, не пов'язаних з конкретною геодинамічною обстановкою, механізми деформування: вигин компетентного шару і загальна неспіввісна течія шаруватої товщі. Послідовне зняття цих деформацій у зворотньому напрямку, а також урахування наявних розломних зсувів призводять у підсумку до одержання розрізу осадового басейну у вихідному стані. Приклад відновлення басейнових розрізів для Кросненської і Скибової зон у центральному перетинанні Українських Карпат дав результат по довжині, що не виходить за рамки виконаних раніше реконструкцій для збалансованих розрізів: 4-х кратне збільшення сучасної довжини – подібність, що відбиває скоріше виконання законів геометрії. Неформальний зміст побудов на основі незбалансованих, складчастих розрізів полягає в можливості залучення різноманітних механізмів деформування чохла і вільний підбор моделей геодинамічного розвитку.

3. Виконання прямої задачі реконструкції незбалансованого розрізу у статті було здійснено на основі чисельного моделювання у рамках механіки суцільного середовища. За допомогою моделювання був відновлений хід розвитку типової складчастості при наростаючому стиску чохла, нерівномірному ковзанні в його підлозі, за участю розломів і без. Подальше просування у цьому напрямку вимагає значного збільшення спектра відтворених сторін процесу, що враховує літофаціальну складову, участь фундаменту, збільшення масштабу моделювання до літосферного рівня з допущенням розмаїтості геодинамічних умов – усього того, що в стані забезпечити розмаїтість видимих на розрізах структурних форм.

4. Крім домінуючої на сьогоднішній день акреційної моделі, пов'язаної із умовами субдукції літосфери (суб)океанічних басейнів, до інтерпретації тектонічної будівлі Карпат, як і раніше, можливе застосовування ідей про реалізацію гравітаційної нестійкості, колізійного стискання, а також їхньої комбінації. Саме розгляд складчастості у всім різноманітті форм, як доводять експерименти, дає підстави для подальшого залучення цих обстановок. У загальних умовах бічного стиску, що викликає інверсію осадового басейну, можуть виявлятися відмінні риси, що розкривають присутність того чи іншого геодинамічного процесу. Деформації колізійного (більш-менш рівномірного) стиску чохла разом із фундаментом, будуть відповідати , в першу чергу симетричні складки, включаючи специфічні гребньовидні структури, – тип, що розповсюджений у межах Кросненської і Сілезської зон. Унаслідок реалізації гравітаційної нестійкості, як добре відомо, може виникати моновергентний складчасто-насувний парагенезис, близький акреційному тектонотипу (тобто насуви й асиметричні антикліналі у висячому крилі, насувні луски й інші моновергентні форми пликативної і диз'юнктивної деформації, формування яких обумовлено блокуванням зсуву у підошві чохла); тут відмінним специфічним індикатором гравітаційного потоку може служити більша розмаїтість величин і характеру деформацій, включаючи присутність складок зворотної вергентности. Також може мати відношення до гравітаційного тектогенезу тісне сусідство і взаємна компенсація зі структурами розтягання в тилу орогена, що і спостерігається в Панноно-Карпатах.

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Конфлікт інтересів: автор повідомляє про відсутність конфлікту інтересів

Декларація про використання генеративного штучного інтелекту: автор підтверджує, що під час підготовки рукопису не використовувалися інструменти штучного інтелекту.

Conflict of Interest: The author declare no conflict of interest.

Declaration of use of generative artificial intelligence: The author confirms that no AI tools were used during the preparation of the manuscript.

Reconstruction of unbalanced cross-section of Flysch Carpathians

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ABSTRACT

The purpose. Making up on an example of Flysch Carpathians numerical experiments in sphere of palinspastic restoration of fold-and-thrust orogens without entering any essential changes into initial geological cross-section or structure scheme, that first of all concerns folds.
Method. Investigations are based on application of most general, conceptually neutral mechanisms of folding: bending and uncoaxial flow. Cross-section reconstruction is executed by means of consecutive removal of the specified deformations, and indemnifications of thrust movings. The decision of a direct problem of reconstruction is based on numerical modelling of folding in a sedimentary cover; faults displacements were artificially entered as independent components of the general process of viscous-plastic deformations.
The results. Full restoration of Ukrainian Flysch Carpathians for the central cross-section of Krosno and partly Skiba zones is made, the size of the general 4-times orogenic horizontal reduction is obtained, the approximate configuration of initial basin profile is restored. No contradictions are finding by comparison of the received results with the data of reconstruction by the balansed profiles, but addition to them is possibility to tracking evolution of presented folded structures.
In the direct problem series of numerical experiments on reproduction typical asymmetric flexural folds, fold-thrust paragenesis, and also the vertical symmetric folds are maid conditioned by horizontal reduction of a cover. It is shown that for their formation presence of a competent layer and the set conditions of sliding at a base is necessary. On the basis of the received experimental data approximate restoration of process of formation typical tructural forms for the central crossing of Krosno zone has been made.
Scientific novelty. It is shown, that for palinspastic reconstruction of folded belt structural profiles can be used in that kind in what they are presented by authors, without preliminary processing by balancing. The offered program of reconstruction is the antithesis to methodology of the balanced cross-sections which can be followed by the synthesis, she itself is attempt to balance modern structural-tectonic approaches.
Folds numerical modelling gives a full spectrum of characteristics of deformation process: angles and sizes of the main stresses, sizes of deformations of compression and shear, etc., that allows to spend effective comparison of experimental conclusions with data of natural objects studying.
The informal maintenance of constructions on the basis of unbalanced profiles consists in possibilities to attracting various mechanisms of deformation of a sediments and free selection of geodynamic models. Except dominating for today accretion model connected with subduction of a basins crust, ideas about realisation of gravitational instability and collisional compression, and also their combination may to be applied; consideration of folding in all variety of forms gives the grounds to attraction of these conditions to interpretation of a tectonic structure of Carpathians.

ARTICLE INFO

Manuscript received
11 November 2025

Revised manuscript received
14 May 2026

Manuscript accepted
25 May 2026

Available online
30 May 2026

Keywords:

folds belts, palinspastic reconstructions, unbalansed crossection, fold-and-thrust deformations, buckling, uncoaxial flow, numerical modeling, stressed state, Flysch Carpathians.

In cites: Gonchar Victor (2026). Reconstruction of unbalanced cross-section of Flysch Carpathians. *Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology*, (64), 49–60. https://doi.org/10.26565/2410-7360-2026-64-04 [In Ukrainian]

https://doi.org/10.26565/2410-7360-2026-64-05

UDC 553.43:551.263:550.4

Geological and genetic peculiarities of the formation of porphyry copper mineralization in the Goshgarchay porphyry-epithermal system (Lesser Caucasus, Azerbaijan)

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ABSTRACT

Problem statement. The third defended point. Substantiation of long-term and multi-stage formation of endogenous ore deposits and occurrences of geological and physico-chemical conditions of mineralization, ore-metasomatic and geochemical zoning in porphyry-epithermal systems.
Formulation of the purpose. Investigation of the geological and genetic characteristic of the formation of cooper-porphyry mineralization in the Goshgarchay porphyry-epithermal system based on geological and physical-chemical criteria.
Research methods. Rock samples were studied by inductively coupled plasma mass spectroscopy (ICP-MS) (Turkey, Izmir). Analytical studies were performed at the USGS Analytical Laboratory of the US Geological Survey (USGS, Denver). Using certified inhouse standars. Isotope analyzes were performed at the Stable Isotope Laboratory at the University of Arizona (Thermo Quest Finnigan Delta Plus XL). Fluid inclusion studies were carried out in the Laboratory of Istanbul University.
The main material. The basis of the factual material was a collection of samples (about 150 pieces) taken inside and around the stockwork with vein- impregnated mineralization and on its flank to a depth of more than 500 m from the surface. The samples were used to make petrographic thin sections and plates polished on both sides for the study of fluid inclusions, and the rest of these samples were clustered and dispersed on sieves.
Conclusions. The characteristic elements of the intrusions are Cu, Pb, Zn, Ag, Mo. Fluid inclusions in minerals associated with the ore, including Cu sulfates and quartz show that the ore-forming fluid may have a mineralization of 2-5 wt.% NaCl eq., although there may be a marked increase in mineralization with depth to 20-30 wt.% NaCl eq. below the ore zone. Each type of mineralization corresponds to quite a certain range of physicochemical parameters and chemical composition of the ore-forming fluid. Sulfides, which complete the ore process of the quartz-sphalerite-chalcopyrite stage, are characterized by a marked enrichment in the heavy sulfur isotope δS34 with a rather narrow range of δS34 variation from +0.1‰ to +0.7‰. Porphyry copper ores were formed in a post-magmatic hydrothermal environment at a depth of about 0.5-1.0 km at a temperature range of 365-200°C. Based on mineralogical, geochemical, fluid inclusion and sulfur isotope data, the Goshgarchay porphyry copper field represents a late stage of peripheral magmatic and hydrothermal mineralization, likely underlain by a latent porphyry field. The formation of the Goshgarchay porphyry copper deposit began with the occurrence of primary quartz veins at a depth of 2.5-3 km at a temperature of 400-250°C. Porphyry copper ores were formed in a post-magmatic hydrothermal environment at a depth of about 0.5-1.0 km at a temperature range of 365-200°C. The complexity of the objects shows the high potential of porphyry copper areas and selected areas in the rank of potential ore fields.

ARTICLE INFO

Manuscript received
12 March 2026

Revised manuscript received
17 April 2026

Manuscript accepted
25 May 2026

Available online
30 May 2026

Keywords:

Goshgarchay porphyry-epithermal, geochemical, genetic characteristics, rare earth elements, hydrothermal-metasomatic alterations, evolution environment, genetic features, porphyry copper mineralization, propylitic alteration.

Introduction

Porphyry copper fields are among the major sources of Cu, Mo, as well as Au, Ag, Sn with associated Re, W, In, Pt, Pd and Se. From 50 to 60% of world copper production falls to their share and more than 95% of world Mo production. The patterns of placement and conditions of formation of porphyry copper fields have been studied by many researchers. First of all, numerous studies on porphyry copper fields are aimed at revealing the peculiarities of their formation in different

In cites: Mansurov Mamoy (2026). Geological and genetic peculiarities of the formation of porphyry copper mineralization in the Goshgarchay porphyry-epithermal system (Lesser Caucasus, Azerbaijan). *Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology*, (64), 61–77. https://doi.org/10.26565/2410-7360-2026-64-05



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geodynamic settings, creating descriptive and genetic models as a basis for effective prediction, prospecting and assessing areas with economically important mineral fields [9, 26].

Porphyry copper fields of the Lesser Caucasu s are most intensively occurred in the Lok-Karabakh and Miskhan-Zangezur zones, which differ significantly in the geodynamic regime of formation and metallogenic zonation.

Formation of the Lok-Karabakh zone deposits occurred in island-arc conditions in connection with volcano-plutonic complexes, the Miskhan-Zangezur zone deposits in connection with granitoid complexes of the stage of tectonic-magmatic activation of the Iran median massif.

Accordingly, these fields in the Lesser Caucasus are characterized by double occurrences. It occurred in a narrow time interval in the Lok-Karabakh island arc (late Jurassic-early Cretaceous), and in the upper Eocene-Miocene in the Miskhan-Zangezur. Porphyry copper fields are observed in Murovdag, Gadabay, Mehmana, copper- and molybdenum-porphyry fields in Ordubad and Dalidag ore districts.

The Murovdag ore district is one of the most promising ore districts of the Lesser Caucasus folded mountain structure and is characterized by the occurrence of a number of fields and ore occurrences that are promising for copper, molybdenum, gold, lead, zinc and other minerals. There are also several fields and ore occurrences of the porphyry copper type, in which copper ore resources can be classified as large fields. The most studied is the Goshgarchay porphyry copper field, where exploration work was carried out, which allowed to identify it as very promising.

Factual materials and research methods

The basis of the factual material was a collection of samples (about 150 pieces) taken inside and around the stockwork with vein-impregnated mineralization and on its flank to a depth of more than 500 m from the surface. The collection includes samples collected from gabbroids, quartz diorites, quartz veins with galena-sphalerite-chalcopyrite mineralization. The samples were used to make petrographic thin sections and plates polished on both sides for the study of fluid inclusions, and the rest of these samples were clustered and dispersed on sieves. Atomic absorption spectrometry on a Perkin Elmer instrument allowed to quantify elements such as Cu, Mo, Cr, Ni, Co, Pb, Zn, Sr, As, Bi. Rock samples were studied by inductively coupled plasma mass spectroscopy (ICP-MS) (Turkey, Izmir). Analytical studies were performed at the USGS Analytical Laboratory of the US Geological Survey (USGS, Denver). Using certified inhouse standars. Isotope analyzes were performed at the Stable Isotope Laboratory at the University of Arizona (Thermo Quest Finnigan Delta Plus XL). Fluid inclusion studies were carried out in the Laboratory of Istanbul University

The results of spectral, atomic absorption and chemical analyzes were used when solving the issues of determining the main ore components and its genetic and geochemical properties in the Goshgarchay porphyry-epithermal system. The number of testing points within the porphyry-epithermal system was up to 1000. Their distribution was equal within the area. Rooty exposures were tested by natural outcrops and exploratory mountain excavations (trenches, pits, wells). All testing points were accompanied by geological-petrographic descriptions.

Geological setting

The formation of the secondary folding arc of the Lesser Caucasus, the compaction towards the Anatolian and Iranian plates, the longitudinal and transverse diagonal dislocations, the formation of systems, the transverse uplift zones of the Caucasus are related to the giant rupture fractures-transverse faults that control the occurrence of its orogenic effusive magmatism. The Lesser Caucasus is the main part of the Tethys orogenic belt, which stretches from the Black Sea to the Caspian Sea. This ribbon-like belt, extending to Asia, connects the Western and Central metallogenic belts of Tethys [23, 30]. The Lesser Caucasus corresponds to the collision zones of the microcontinents marked by the subduction of the oceanic crust of the Lesser Caucasus limb of the Mesotethys, covering the edges of the Eurasian plate in the north and the Iranian plate in the south [9, 23] (Fig. 1).

According to the concept of the formation of the Lesser Caucasian mature island arc on the subduction zone lying to the north, from beginning the Middle Paleozoic and including the Middle Jurassic, researchers believe that since the Late Jurassic, the subduction front shifted to the north, and then sharply changed its direction to the south-southwest [9]. The Lok-Karabakh zone is located parallel to the Kura depression, and is bounded by large thrust and upthrust-dislocations (Murovdag, Karabakh) that surround the ophiolite zone to the southwest and separate it from the Goycha-Hakara zone. This zone is intermittently characterized as an island arc, which is distinguished by calc-alkaline magmatism as a result of subduction of the Neotethys from the Jurassic to the Cretaceous. It is divided into different segments by transverse faults characterized by strong volcanism in Bajocian-Bathonian and Kimmeridgian. The model of geodynamic development of the region, which was proposed by a number of researchers [9], allows to explain sufficiently the petrological seriality and petrochemical polarity in the development of

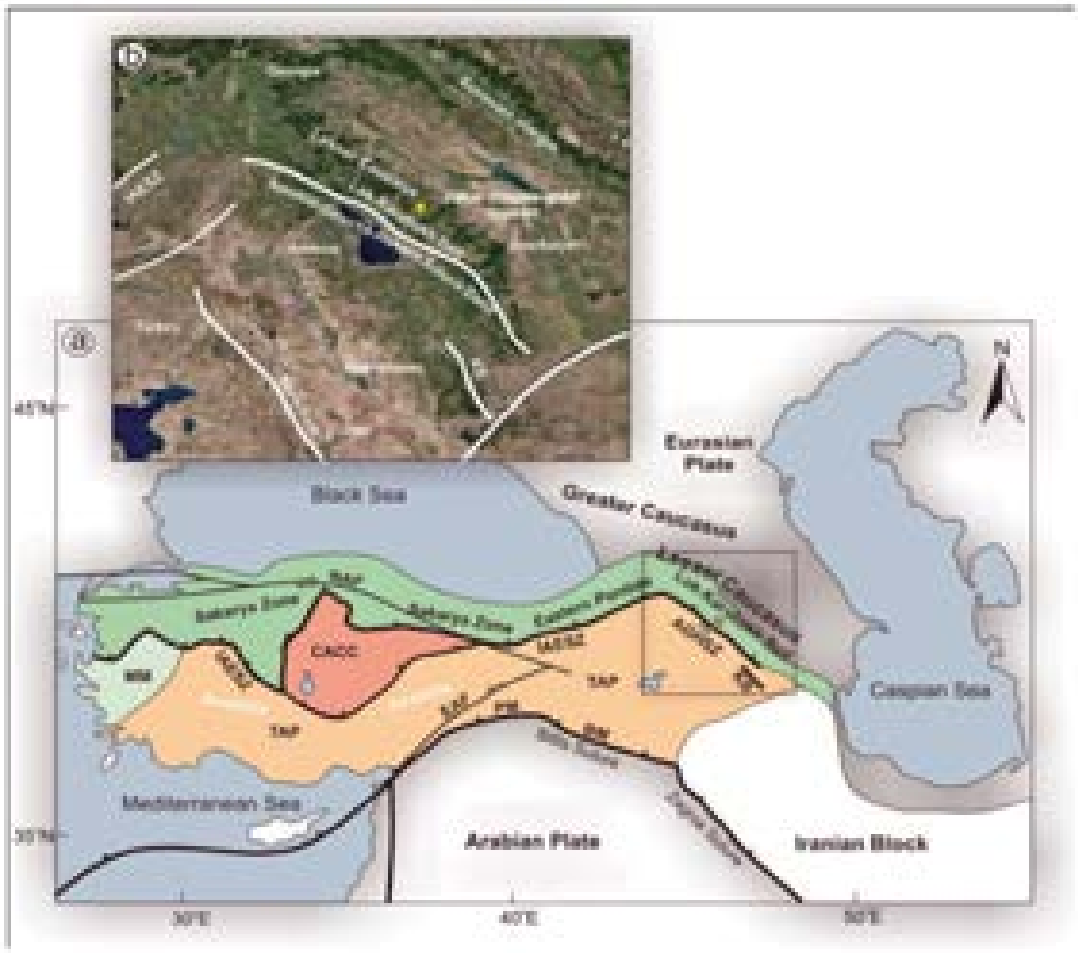


Fig. 1. Simplified tectonic map of the Caucasus area, with main blocks and suture zones

magmatism, the observed metallogenic zoning – Late Kimmeridgian and Alpine tectono-magmatic cycles and the formation of metallogenic epochs in the Lesser Caucasus. Zonally developed copper-pyrite and polymetallic, porphyry copper, skarn-magnetite, gold-polymetallic, copper-molybdenum-porphyry, antimony-mercury-arsenic and other ore deposits and occurrences were formed within the region [11].

The principles of segregation and study of the ore-magmatic system of the region are currently considered the superior and more informed direction in the theory of endogenous ore formation with optimal criteria for the search and prediction of endogenous ore deposits.

The main goal for the purpose of metallogenic research and distinguishing the ore-magmatic system is to study the regularity of the formation and location of mineral deposits and the evolution of geological processes and their spatial and temporal relationship, and the main element is the processes of magmatism and mineralization.

The analysis of materials on non-ferrous and noble metal systems in the Lok-Karabakh mature island arc shows that the ore-magmatic system develops on a single principle with sour rocks of Late Jurassic-Early Cretaceous magmatism and has an asymmetric zonal structure. They are highly metallic, promising for noble and non-ferrous metals, and are located in certain areas of island arc volcanism, forming a general zonation.

The Murovdag anticline subzone extends from west to east along the watershed of the Shahdag and Murovdag ranges, covering the Shahdag, Gamish and Murovdag highlands. Most researchers consider this structure as an integral part of the Lok-Karabakh fold zone. According to E.Sh.Shikhalibeyli [27], the second-order Murovdag anticlinorium is located after the Gamish-Toraghaychay thrust and is connected to the first-order Goyche-Hakara synclinorium, and this thrust reflects the deep fault zone and is separated from the eastern Shahdag range by the depth-specific Karabakh fault. The geological structure of anticlinorium is composed of Middle Jurassic volcanogenic formations [9, 27].

Large transversal depth faults within the anticlinorium are represented by the Goygol-Khoshbulag faults in the west, and the Murovdag-Zod faults in the eastern flank. Faults are characterized by the older NW (280-300°), near meridional (330-10°) and meridional, and relatively young near latitudinal (80-100°) and latitudinal directions [10].

Intrusives of the Murovdag group were divided into Goshgardag and Gizilarkhaj groups by R.N.Abdullayev [1] according to their geological position and spatial location. Intrusives of the Goshgardag group are located on the eastern and western slopes of Goshgardag Mountain, at the junction of the Balaja and Boyuk Qashgachay rivers. Outcrops of the Ojagdag intrusive are represented by transversely layered bodies, as well as small stock-like bodies, and they are represented petrographically by quartz diorite, gabbro-diorite, a small amount of diorite, gabbro and banatites [9].

Intrusive massifs were opened at a shallow depth by erosion processes, and only the crust of the massif participates on the upper surface. The contact surface of the intrusive is rough and dips at an angle of 55-65° towards the host rocks. This factor shows that intrusives can be attributed to solid bodies expanding at depth. T.Ab.Hasanov [14] discovered stock-shaped and dyke-shaped small outcrops of ultramafic rocks (hyperbasites) among the Early Bajocian volcanites at the junction of Boyuk and Balaja Gashgachay rivers.

The chemical and normative mineral composition of the rocks of these massifs with the most important petrochemical characteristics are given in Table 1.

The rocks in the classification diagram (Na_2O+K_2O)-SiO_2 occupy the field of rocks of normal alkalinity, which allows them to be classified as a normal petrochemical series (Fig. 2). The described classification diagrams of the rock are mainly concentrated in gabbroid fields. The diagram shows that they are compactly arranged. Other petrographic rock types or differentiates are located in the fields of quartz diorites, and according to the normative mineralogical composition here, the content of albites increases significantly, in accordance with this, the content of basic plagioclases decreases significantly [9].

According to new petro-geochemical data, it was determined by V.M.Babazadeh et al. (2008) that ultramafic volcanic rocks – picrites, picrobasalts and picrodolerites occur in this region, and their age corresponds to the Kimmeridgian Age of volcanism. Also, picrobazalts are also found in the form of thin subvolcanic bodies among Kimmeridgian volcanics within the Elbeydash syncline (Abdullayev, and others 1988).

Here, Kimmeridgian vulcanites and picrobasalts are subalkaline and are associated with trachyandesite and trachydasite. According to M.A. Mustafayev, the amount of alkali in these rocks increases to 7.40-9.0%. According to their composition (MgO – 15-20%; K_2O – 0.9-2.5%; Ni – 210 g/t; Cr – 36-400 g/t), these rocks correspond to picrite and picrobasalt [9].

As can be seen from the petrochemical analysis, the Late Jurassic (Kimmeridgian) - Early Cretaceous (Neocom) multiphase intrusives are composed of gabbroid and quartz diorite phases. The latter are associated with monzodiorites, monoquartz diorites and syenites. Each of these phases is distinguished by its own mineralization.

The intrusives of Murovdag complex are located between the calc-alkaline trend and the alkaline trend in the AFM diagram. The calc-alkaline trend corresponds to the direction of alkaline area, and the tholeitic trend corresponds to the direction of ferruginous area. As it can be seen, the evolution of magma took place in a fairly wide variation of alkalinity and iron content. Picrite and picrobasalts are low in titanium (TiO_2 - 0.40-0.57%) and potassium (K_2O-0.06-0.42%) according to their petrochemical properties. Besides, high amounts of iron oxide (FeO-10.15-16.10%) and low amounts of Ca, Mn and Al are observed in all analyses [9].

Bajocian basalt-rhyolite, Bathonian andesite-dacite-rhyolite, and Late Jurassic-Early Cretaceous basalt-andesite-dacite formation are developed within Murovdag anticlinorium. Bajocian volcanics of both complexes belong to sodium (Na_2O/K_2O>4) and potassium-sodium (Na_2O/K_2O=0.4-4.0) series [1, 9].

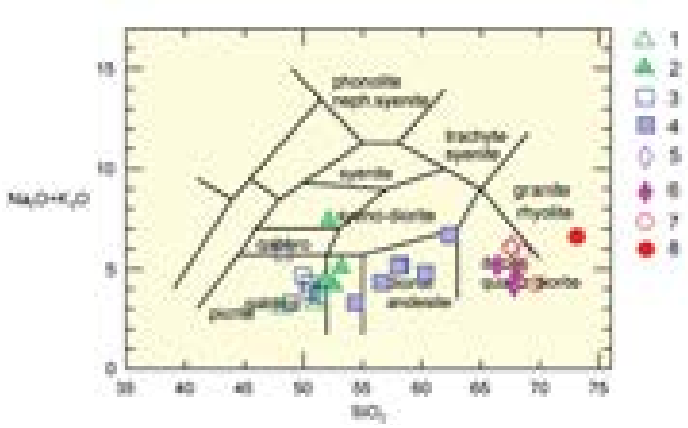


Fig. 2. Position of rocks of igneous complexes on the classification diagram (Na_2O+K_2O)-SiO_2 of the Murovdag anticlinorium: 1 - gabbro-norites, 2 - gabbroids, 3 - gabbro, 4 - quartz diorites, 5 - granodiorites, 6 - dacites, 7 - rhyodacites, 8 - rhyolites

The determining peculiarities of rare earth elements in the metasomatites and host rocks of the Goshgarchay ore-magmatic system were reviewed and it was determined that all rocks, including metasomatic rocks are characterized by a slight advantage of light lanthanoids over heavy lanthanoids. The distribution of rare-earth elements in host rocks and metasomatites of the ore district is listed in table 2. All docks, including metasomatites, ore characterized by slight LREE predominance over HREE. The ratio of La/Yb is 1.4-4.6. A significant advantage of light lanthanides over heavy ones is observed only in diorites, La/Yb=13.4. The ratio of Ce/Ce* is 0.81-1.03 in

Table 1

Chemical composition of rocks of igneous complexes of Murovdag anticlinorium

	1	2	3	4	5	6	7	8
SiO2	48.16	50.93	51.06	51.64	53.19	52.52	52.17	51.84
TiO2	0.53	0.2	0.47	1.04	0.38	1.48	0.46	1.66
Al2O3	19.63	17.79	19.14	16.87	16.48	17.87	21.88	17.45
Fe2O3	10.27	3.9	3.46	3.77	5.76	2.85	3.16	4.47
FeO	3.06	5.6	5.02	4.44	5.09	5.07	4.87	4.84
MnO	0.14	0.13	0.14	0.09	0.08	0.03	0.0	0.13
MgO	3.42	6.04	5.8	5.42	4.22	3.93	3.43	5.02
CaO	12.13	10.01	9.24	10.79	9.63	9.48	5.43	8.04
Na2O	2.27	2.56	3.44	3.63	4.54	3.43	4.53	3.74
K2O	0.79	0.74	0.44	0.64	0.57	0.76	2.87	0.73
P2O5	0.0	0.0	0.043	0.0	0.0	0.0	0.0	0.0
I	0.44	2.08	1.07	2.14	0.62	2.37	1.66	2.03
Σ	100.84	99.98	99.32	100.47	100.56	99.79	100.66	99.95

	9	10	11	12	13	14	15	16	17	18	19	20
SiO2	51.35	50.56	50.45	49.91	48.96	48.27	54.38	58.18	56.6	58.03	60.28	62.33
TiO2	0.25	0.63	0.31	0.51	0.28	0.41	0.66	0.66	0.47	0.12	0.43	0.23
Al2O3	16.55	12.36	18.15	12.98	16.68	21.78	14.37	18.24	16.51	15.01	15.63	13.83
Fe2O3	7.18	10.52	5.07	7.52	9.18	5.38	6.77	2.23	2.5	5.66	3.37	4.42
FeO	6.23	7.42	4.63	8.88	4.37	3.62	5.06	2.63	4.95	4.08	3.73	2.73
MnO	0.12	0.14	0.06	0.14	0.12	0.07	0.04	0.11	0.14	0.0	0.06	0.0
MgO	2.82	3.97	5.42	3.36	5.06	4.02	5.03	3.67	4.7	2.31	2.81	3.12
CaO	10.33	9.64	7.13	10.53	10.66	6.13	6.95	7.13	7.1	6.92	5.35	8.65
Na2O	3.36	3.13	3.43	4.08	2.73	3.88	2.28	3.96	3.2	3.32	3.46	6.22
K2O	0.35	0.73	0.88	0.61	0.58	1.87	1.0	1.23	1.12	1.82	1.33	0.48
P2O5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.09	0.0	0.0	0.0
I	2.22	1.72	4.02	2.06	1.29	4.26	3.2	1.32	2.2	3.04	2.32	0.86
Σ	100.76	100.82	99.55	100.58	99.91	99.69	99.74	99.36	99.58	100.31	98.77	102.87

	21	22	23	24	25	26	27	28	29
SiO2	68.61	67.64	67.95	67.82	66.42	69.66	68.25	67.47	73.12
TiO2	0.21	0.56	0.25	0.26	0.27	0.37	0.37	0.37	0.37
Al2O3	16.34	15.36	15.12	16.83	16.98	14.51	14.63	14.91	13.16
Fe2O3	1.96	2.03	2.28	2.26	2.23	1.73	1.83	1.68	2.17
FeO	2.54	2.56	1.47	1.98	1.75	1.56	1.28	1.86	0.98
MnO	0.12	0.12	0.07	0.02	0.09	0.07	0.06	0.05	0.06
MgO	0.0	1.06	1.77	1.78	2.43	1.73	1.87	2.68	1.66
CaO	4.0	3.54	5.16	3.62	4.27	5.12	4.83	4.23	0.82
Na2O	3.66	3.67	3.28	2.63	3.46	2.96	3.46	3.36	6.02
K2O	2.17	2.48	1.37	1.47	1.74	1.25	1.63	2.68	0.61
P2O5	0.0	0.0	0.06	0.08	0.06	0.06	0.07	0.07	0.07
I	0.56	0.76	0.98	1.03	0.95	0.72	0.97	0.88	0.68
Σ	100.17	99.78	99.76	99.78	100.65	99.74	99.25	100.24	99.72

Note: 1-4 – gabbro-norites, 5-8 – gabbroids, 9-14 – gabbro, 15-20 – quartz diorites, 21-25 – dacites, 26-28 rhyodacites, 29-rhyolites

metasomatites [16]. Absence of Ce anomaly in metasomatites may show the dominance of magmatogenic fluids in the composition of fluids that formed metasomatites and ore mineralization .The determining trends of rare earth elements in metasomatites reflect the determining characteristics of these elements in primary rocks (gabbroids, diorites and andesites) subjected to metasomatic alterations. However, the maximum value of the sum of rare earth elements is observed for diorites (91 g/t), and the minimum for gabbro (6.5 g/t). Diorites enriched in light lanthanides occur with increasing ratio of Ce/Yb. In contrast to other rocks, the ratio for these rocks is 25.7, which shows the magmatogenic origin of the fluids [15] (Fig.3).

Analysis of obtained data shows that the metasomatites and host magmatic rocks in the studied deposits have similar REE distribution patterns, which may indicate that similar magmatic rocks were protoliths for the metasomatites. This also follows from the systematic distribution of insompatible elements. In the La-Nb and Sm-NB diagrams, the metasomatites and host rocks define a common trend (Fig.4).

Analysis of the data shows that the host rocks and metasomatites have close determination parameters of rare earth elements and both types of rocks have uniform fluid nature. By characterizing the determination of rare earth elements in the igneous and metasomatic rocks of the Goshgarchay ore-magmatic system, the following conclusions can be come: 1) metasomatites and host rocks are characterized by the predominance of light rare earth elements over heavy elements, rare earth elements have a uniform genesis; 2) rare earth elements show different mobility during the formation of ore metasomatites: light rare earth elements (La to Sm) show minimal mobility, and heavy rare earth elements show maximum mobility; 3) the fact that metasomatites and host rocks have similar determination parameters

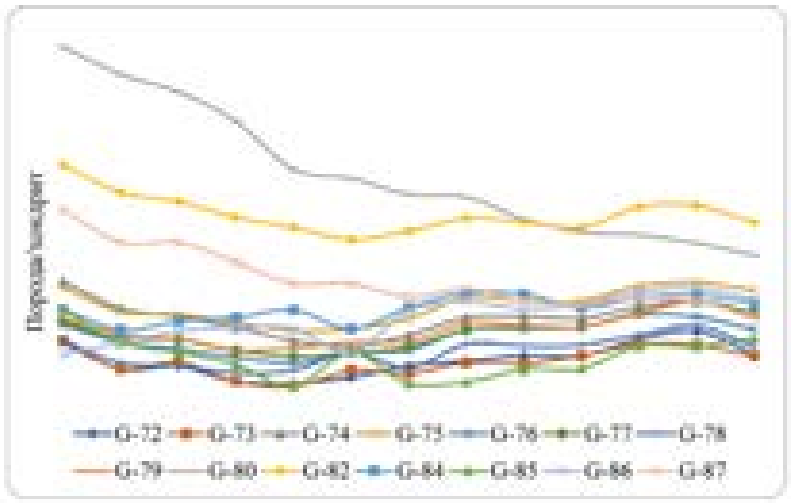


Fig. 3. Chondrite-normalized REE distribution patterns for the magmatic and merasomatic rocks of the Murovdag ore district. Normalizing valuues are from (Sun, McDonough, 1989). For sample number, see table 2

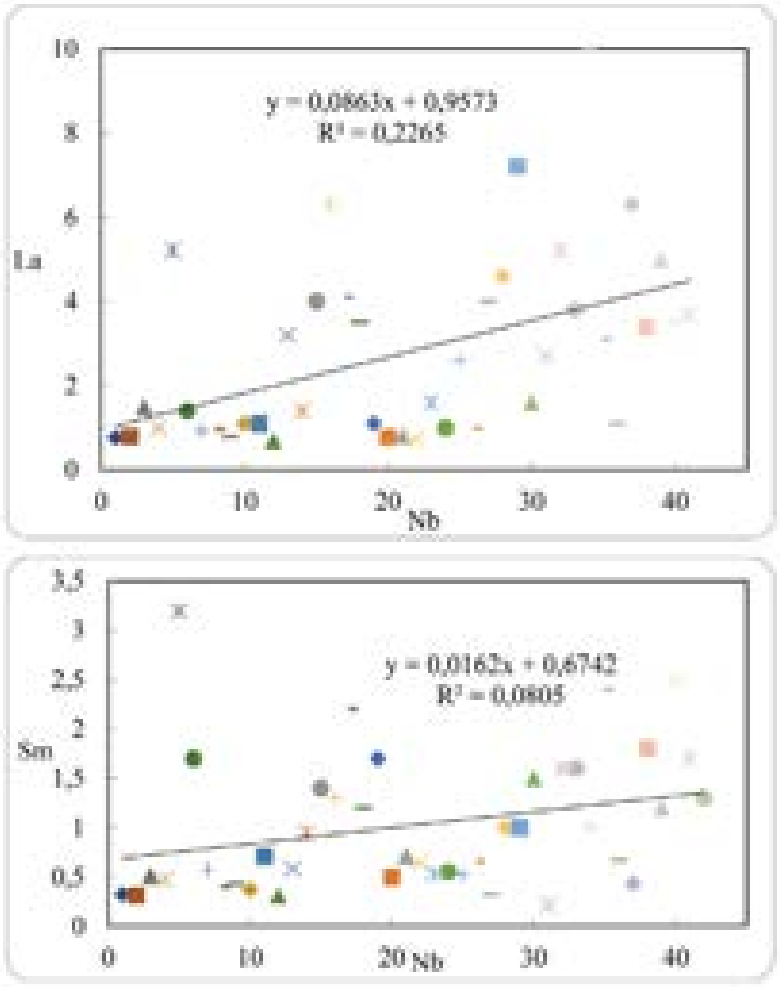


Fig.4. The La-Nb and Sm-Nb diagrams for the magmatic and metasomatic rocks of the Murovdag ore district. Intrusive rocks (gabbro, gabbro-dolerites, diorites, quartz diorites);volcanic rocks (basalts, andesitis, bazalts-andesites); metasomatic rocks (scondary quartzites, ore secondary).

Table 2

The contents of rare – earth elements in the maqmatic and metasomatic roeks of the Murovdag ore district

Compo-nent	Gabbro				Diorite	Basalt	Andesite	Secondary quartzite	Ore secondary quartzite				Copper-porphy-ry ore
	G-72	G-73	G-74	G-79	G-80	G-82	G-75	G-76	G-78	G-84	G-86	G-87	G-85
La	0,76	0,78	1,80	1,00	18,6	5,20	1,40	0,93	0,77	1,10	0,85	3,20	1,10
Ce	1,51	1,50	2,90	2,20	36,00	10,0	2,81	2,01	1,62	2,31	2,01	5,81	2,01
Pr	0,23	0,26	0,42	0,33	4,60	1,41	0,40	0,28	0,23	0,38	0,350	0,91	0,27
Nd	1,00	1,00	1,80	1,40	16,50	5,81	1,91	1,31	1,11	2,01	1,81	3,60	1,20
Sm	0,33	0,32	0,52	0,46	3,20	1,72	0,56	0,41	0,36	0,72	0,55	0,96	0,32
Eu	0,14	0,13	0,19	0,18	1,12	0,56	0,23	0,16	0,16	0,23	0,15	0,35	0,16
Gd	0,53	0,47	0,74	0,67	3,32	2,22	0,86	0,63	0,53	0,97	0,95	1,10	0,44
Tb	0,10	0,097	0,15	0,16	0,57	0,45	0,21	0,13	0,13	0,22	0,15	0,21	0,090
Dy	0.71	0,65	1,12	1,00	3,12	3,01	1,31	0,96	0,81	1,41	1,21	1,30	0,63
Ho	0,15	0,15	0,23	0,23	0,61	0,62	0,28	0,23	0,17	0,26	0,25	0,26	0,13
Er	0,55	0,54	0,80	0,73	1,71	2,31	1,01	0,74	0,58	0,87	0,93	0,86	0,53
Tm	0,093	0,082	0,14	0,14	0,24	0,35	0,15	0,12	0,11	0,13	0,15	0,14	0,07
Yb	0,491	0,480	0,76	0,74	1,42	2,01	0,97	0,63	0,52	0,86	0,85	0,73	0,57
∑REE	6,594	6,459	11,57	9,24	91,01	35,67	12,10	8,54	7,10	11,47	10,21	19,43	7,53
La/Yb	1,572	1,646	1,947	1,387	13,356	2,60	1,427	1,467	1,491	1,293	0,763	4,323	1,895
Lan/Ybn	1,126	1,181	1,396	0,995	9,582	1,863	1,023	1,052	1/068	0,927	0,547	3,102	1,561
Eu/Eu*	0,968	1,105	0,902	1,025	1,026	0,901	0,952	1,041	1,195	0,805	0,695	1,071	1,421
Ce/Ce*	0,855	0,844	0,887	0,935	0,985	0,892	0,882	0,928	0,862	0,808	1,027	0,855	0,865
∑(REE)n	35,518	34,581	56,537	49,476	343,65	172,10	64,395	45,571	38,803	61,694	56,569	88,65	60,215
Ce/Yb	3,060	3,126	3,765	3,056	25,713	5,01	2,856	3,124	3,017	2,706	2,246	7,836	3,447
Eu/Sm	0,405	0,450	0,353	0,403	0,344	0,334	0,384	0,424	0,458	0,307	0,292	0,377	0,547

Eu/ Eu* = Eu/((Sm+(Gd)/2); Ce/Ce* = (Ce_N/ ($2La_N$ + Sm_N + Sm_N)/3)

indicates that analogous igneous rocks are the substrate for metasomatites [20].

Murovdag ore region is characterized by the prospect of porphyry copper, copper-pyrite, copper-polymetallic and other types of ore deposits and occurrences. Two ore-magmatic systems are separated within the ore region: Goshgarchay and Gizilarkhaj. The first of these includes the Goshgarchay and Goshgardagh porphyry copper, as well as the Chanakhji and Zivlan copper- pyrite deposits and occurrences. The second includes the Gizilarxhaj, Kecheldag, Jamillibulag, Erik-Manuc and Elbeydash porphyry copper and copper-polymetallic deposits and occurrences. We tried mainly to investigate the geological-genetic characteristics of the first ore-magmatic system.

Porphyry copper mineralization covering Goshgarchay, Goshgardag, Gizilarkhaj and other deposits and occurrences in the Murovdag ore region is spatially and genetically associated with the granitoid intrusive of the same name. The intrusives that make up the ore-magmatic system, the Goshgarchay complex that forms the effusive-pyroclastic complex and creates a contact-thermal relationship with them, consists of granitoid intrusives (Goshgardag, Ojagdag, Balaja Goshgardag) and their dyke systems.

Fracture structures with different directions that create the block structure of the ore-magmatic system play an important role in the spatial determination of porphyry copper and copper-polymetallic mineralization in the ore region [3].

Goshgarchay porphyry copper deposit

The deposit is considered the most promising deposit of the ore-magmatic system of the same name and is located on the southwestern flank of the Murovdag anticlinorium, adapted to the endo- and exocontact zone of the gabbro-diorite-garanodiorite formation intrusive belt.

The closest and Caucasus-oriented faults in the region are considered to be direct ore-bearing structures, and the northwest- oriented faults that cross the Goshgarchay fault from the dependent side are considered to be ore-locating structures. This is explained by the following factors: 1) localization of ore zones at the moment of dependence of fault; 2) ore zone and faults falling in the same direction at a steeper angle; 3) localization of ore zones in small fracture systems and locally significant faults; 4) adaptation of intensively hydrothermally altered rocks and impregnated sulfide mineralization to major faults of subvolcanic masses and dykes [3, 20].

Ore-metasomatic zonation. The zonation of minerals and chemical elements in the ore masses of hydrothermal deposits is directly related to the zonation of wallrock metasomatites. From this point of view, porphyry copper deposits, which clearly show the horizontal and vertical zonation of various formations of ore- forming elements and metasomatites, are considered typical [22].

During the formation of the Goshgarchay massif, the segregation of metal-bearing fluids varied, which led to the formation of a wide propylitization zone related to the initial phase, and then to the formation of potassic, quartz-sericite, and quartz metasomatites and argillization related to the acidic late phase. Most of the formation of industrially important porphyry copper mineralization occurred as a continuation of the occurrence of the early generation of porphyries [2; 3].The late phase of the porphyry is accompanied by intense silicification, which allows to note the possibility of the formation of a “quartz core” in the central part of the deposit.

Three metasomatic zones are separated in the shape of an ellipse around the quartz-diorite porphyry intrusive stock in the structure of the metasomatic column within the Goshgarchay ore- metasomatic system [3, 20]: 1) *the inner zone* was represented by intensely secondary quartzites covering the endocontact and apical part of the porphyry intrusive. According to the mineral composition, this zone corresponds to the quartzsericite facies of the secondary quartzites, and its mineralization is usually weak. A gradual increase in the amount of sulfides is observed with depth, and the amount of Cu increases from 0.01% to 0.15%; 2) *the middle zone* separates as a quartz-sericite-chlorite facies of secondary quartzites. The mineral composition of metasomatites is represented by quartz, chlorite, sericite, epidote, calcite and pyrite. The development of mineralization is particularly characteristic of the quartz-sericite-chlorite facies; 3) *the outer zone* of the metasomatic column was represented by the propylite facies of secondary quartzites. Here, propylitization has a regional distribution. New mineral assemblages represented by chlorite, epidote, albite, sericite, actinolite, and pyrite are widely developed and reflect the regional character of propylitic alteration in the host rocks.

The following main features are observed in the zoning of metasomatites in the porphyry copper deposits of the Goshgarchay ore-magmatic system: 1) positional connection with granitoid porphyry intrusive; 2) replacement of the biotite-kalifeldspath-quartz-sericite-propyllite metasomatite zone; 3) the vertical zoning order of elements is represented by Mo→ Cu→ Co → Ni → Cr → Ag→ Pb → Zn; 4) impregnated -veinlet type of mineralization [3, 14, 28].

A complex geological model of the porphyry system began to be formed as a result of development of numerous geological, petrological and metasomatic indicators. The most perfect of them belongs to R.N. Sillitoe [45]. Besides other types of deposits, the position of porphyry copper deposits is shown in this model. According to this

Table 3

Results of chemical analyses on the main ore caused elements

№	Cu	Mo	Pb	Zn	Sb	As	Ni	Co	Ti	V	Cr	Bi	Ba	Sr
G-72	105.0	0.91	11.11	83.6	0.58	1.8	2.20	0.62	667.0	127.0	1260.0	0.13	50.20	39.8
G-73	248.0	0.82	5.51	1120.0	0.41	1.3	20.7	21.0	689.0	120.0	1340.0	0.07	170.0	42.3
G-74	149.0	0.76	3.67	130.0	0.44	2.0	534.0	84.8	891.0	151.0	1530.0	0.08	57.01	35.5
G-75	88.40	2.21	51.7	173.0	0.96	2.0	321.0	59.3	1230.0	202.0	1520.0	0.14	106.01	69.6
G-76	104.0	0.46	3.63	77.21	0.22	4.2	519.0	85.7	886.0	161.0	1780.0	0.07	59.1	29.8
G-77	66.20	0.68	3.87	124.0	0.20	<1.0	539.0	88.6	949.0	156.0	2210.0	0.07	93.51	30.5
G-78	334.0	1.30	68.2	636.0	0.87	4.5	597.1	95.3	770.0	159.0	2260.0	0.10	582.0	41.2
G-79	116.0	0.66	3.07	68.7	0.25	2.3	492.1	83.6	990.0	196.0	2360.0	0.07	120.0	33.6
G-80	214.0	2.10	13.0	90.0	1.11	5.5	17.8	17.3	6750.0	102.0	261.0	0.15	864.0	699.0
G-82	49.5	1.0	7.92	60.2	0.23	4.8	26.7	20.3	2520.0	323.0	203.0	0.07	48.81	50.0
G-84	15000.0	4.5	6.72	106.0	1.0	5.8	34.8	9.50	1300.0	180.0	719.0	0.87	456.0	240.0
G-85	10900.0	4.51	9.50	49.61	2.2	12.5	34.7	8.40	819.0	123.0	738.0	0.43	95.7	249.0
G-86	20300.0	4.21	6.94	79.31	1.20	7.6	46.3	13.20	1090.0	158.0	251.0	0.34	353.0	196.0
G-87	1350.0	7.20	6.76	35.32	0.53	1.4	15.0	10.0	1160.0	92.3	421.0	0.07	112.0	290.0

Note: G –72-gabbro, G – 73-gabbro, G – 74-gabbro, G –79-gabbro, G – 80-diorite, G – 82 – basalt, G –75-andesite, G –76-andesite, G –77-andesite, G-78-secondary quartzite, G – 84-ore secondary quartzite, G – 85-porphyry copper ore, G – 86-ore secondary quartzite, G – 87-ore secondary quartzite. Rock samples were analyzed by inductively coupled plasma mass spectroscopy (ICP-MS). Analytical studies were carried out in the analytical laboratory of the United States Geological Survey (USGS) (Denver).

model, it can be stated that the main factors of metasomatic alterations in the Goshgarchay ore-magmatic system are small porphyry intrusives of the surrounding ledge, stock and dyke type, the composition of primary rocks, breccia and ore masses, ore-metasomatic zoning, mineralogical composition of ore-bearing metasomatites, etc. [30].

According to the ore-metasomatic characteristics of the porphyry copper deposits of the Goshgarchay ore-magmatic system, the following can be stated: 1) intrusive complexes associated with porphyry copper mineralization belong to the Late Jurassic-Early Cretaceous gabbro-diorite-granodiorite formation according to their geological and petrological characteristics; 2) the segregation of metal-bearing fluids was repeated many times and first led to the formation of a large propylite zone associated with the early phase and then, the formation of potassic, quartz-sericite and quartz metasomatites and argillization associated with the acidic late phase; 3) Metasomatic formations of porphyry copper deposits were represented by the successive occurrence of kalifeldspath, greisen, propylite, secondary quartzite and argillaceous formation; 4) the main volume of industrially important porphyry copper mineralization is controlled by porphyry stocks and breccia masses, and sometimes they carry the ground mass of the ore material [19].

Geochemical peculiarities of ore-forming systems. The study of the geochemical peculiarities of the porphyry copper systems of the Murovdag ore district was based on the results of chemical analysis (Table 3) of the drill-hole cores,

Table 4

Results of factor analysis of geochemical data using the method of main components

Minerals	Factors		
	F 1	F2	F3
Cu	-0,49628	0,2845950	-0,7401
Mo	-0,2032	0,113154	-0,84753
Pb	0,976722	0,02410	-0,13387
Zn	0,400451	0,033847	0,6858260
Sb	1,0606580	0,05587	-0,00528
As	1,2639560	0,1219790	-0,15024
Ni	1,3594420	0,3115810	-0,07492
Co	1,1946370	0,139580	0,4975770
Ti	-0,77458	-2,7810	-0,879241
V	-0,75297	-1,01646	2,8523180
Cr	-1,49068	1,745757	0,5305890
Bi	-0,94605	0,882603	-0,60154
Ba	-0,95204	0,335892	0,055852
Sr	-0,64013	-0,25150	-1,1892

Note: Bold font - significant values of factor loadings

at a depth of 280m on average. Geochemical data on boreholes were processed in the "STATISTIKA" program using the factor analysis method of main components [6; 7]. As a result of the conducted studies, three factors were obtained, reflecting the correlation relationship between fourteen ore elements (Table 3).

According to the weights, the elements are grouped into factors or geochemical associations,

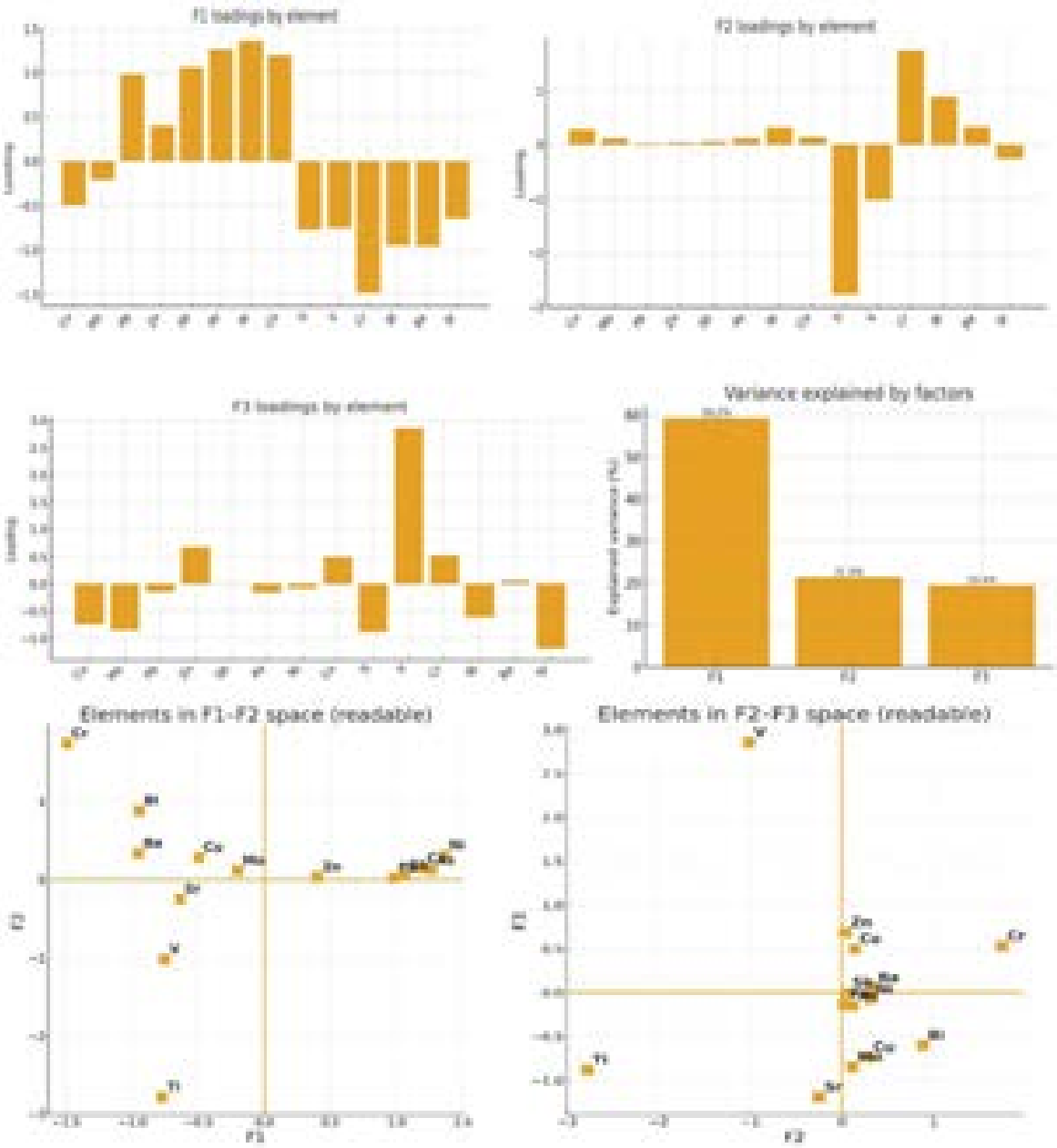


Fig. 5. Dependence graphs of F1, F2 and F3based on the results of factor analysis

which can be compared with mineral parageneses of the main stages of ore deposition [24]. The relationship between geochemical and mineral associations is confirmed by the correlation coefficients between the factor analysis of elements and the sulfide content according to drill-hole core testing data (Table 4, 5)

The values of the factor F1 correlate with the amount of chalcopyrite, bornite and pyrite, which gives grounds to link the geochemical association Cu (Mo, Pb, Sb) with the earliest chalcopyrite-bornite-pyrite mineralization of the porphyry stage of the ore-bearing structure formation.The values of factor F2 corresponding to the Mo (Cu, Pb, Co) association are statistically related to the content of chalcopyrite and molybdenite, which form the main mineral paragenesis of copper-molybdenum-porphyry mineralization. The dependence graphs of F1 and F2 based on the results of factor analysis are shown in Figure 5.

It can be concluded from the materials presented above that the elements are grouped in factors or geochemical associations comparable to the mineral paragenesis of the main ore deposition stage.

The following are considered element-indicators for various factors: 1 – Zn, Cu, Co and Ni – for the constituent factor of host rocks; 2 – Cu, Mo, Co and Ni – for geochemical specialization and primary magma type factors; 3 – Mo -– for the depth factor; 4 – Pb, Mo, Zn and Cu for ore-bearing factor [19, 20].

According to the information by V.Baba-zadeh et al. [3], and M.Mansurov [20], impregnated and impregnated-veinlet type stockwork ore masses have developed in the Goshgarchay porphyry copper deposit. Vein-type ore masses have limited

Table 5

Correlation between sulfide content and factor values based on drill-hole core testing

Minerals	Factors		
	F 1	F2	F3
Chalcopyrite	**0,949830**	**0,1232260**	0,088396
Bornite	**0,9590180**	0,042406	0,129708
Sphalerite	-0,30862	-0,84416	0,003184
Galena	0,057913	0,007865	0,994675
Pyrite	**0,9030980**	0,29172	-0,07574
Molybdenite	-0,61713	**0,5558440**	0,042268
Eigenvalues	3,116916	1,123696	1,021546
Factor loadings	0,519485	0,187283	0,170257

development, are represented by quartz and carbonate veins smeared with pyrite, chalcopyrite and molybdenite minerals, located in shear and hydrothermal alteration zones.

The stockwork-shaped ore masses cover the central part of the deposit and are adapted to the apical and outer part of the porphyry intrusive, more precisely, to its endo- and exocontact zone. Enriched areas are gradually merged and form single ore mass with a complex morphology-stockworks. According to the information by V.M.Babazadeh et al. the existence of two ore horizons, which were enriched with copper mineralization in the deposit and inclined towards the north (15-30°), was determined. The upper ore horizon has a considerable thickness and comes to the surface, while the lower ore horizon lies at a depth of 80-150 m below the surface [3].

The mineral composition of the Goshgarchay deposit is relatively simple and the following ore minerals have been found: pyrite, chalcopyrite, sphalerite, arsenopyrite, melnicovite-pyrite, marcasite-pyrite, marcasite, cobalt-pyrite, enargite, galena, chalcosine, covelline, malachite, azurite, limonite, etc.

According to a number of researchers [3, 20], the formation of the Goshgarchay porphyry copper deposit took place in two stages: hydrothermal- metasomatic ores were deposited in the first stage, and polymetallic ores were deposited in the second stage. According to the composition of copper minerals in the deposit, the following types of ores are distinguished: 1) pyrite-chalcopyrite and chalcopyrite-pyrite; 2) pyrite-bornite-chalcopyrite; 3) dull ores (pyrite)-chalcopyrite; 4) chalcocine-chalcopyrite; 5) native copper. The more common types are chalcopyrite-pyrite and pyritebornite-chalcopyrite ores.

One of the main factors in the formation and location of porphyry copper deposits is their relationships with certain magmatic complexes. From this point of view, the Murovdag anticlinorium reflects the intrusive-volcanic association characterized by andesite volcanism and represented by the gabbro-diorite-granodiorite formation of granitoid intrusive magmatism [3].

The geological-genetic model of the porphyry copper deposits of the Goshgarchay ore-magmatic system is based on geological factors such as the geological characteristics of the host rocks and fault structures, the morphology and occurrence characteristics of intrusive complexes, the mineralized phases of intrusives (porphyry, granitoid), metasomatic alterations and their formational diversity, the morphology and boundaries of ore masses, and thermobarochemical conditions of the mineralization process, stages of mineral formation and mineral associations (intermediate zone-pyrite+chalcopyrite; inner zone and core-pyrite+chalcopyrite+molybdenite), successive concentric zonal alterations, ore-metasomatic zoning, segregation of sulphide mineralization, eruptive breccias and features of erosion section [19, 21].

According to the analysis of existing geological data (structural, magmatic, geophysical, geochemical, etc.) and the results of multi-year studies on the Goshgarchay ore-magmatic system, one of the main features for the building of the geological- genetic model of porphyry copper deposits is the direct connection of the metasomatic alteration zonation of the host rocks with rich ore fields. More obvious examples are potassic, quartz-sericite secondary alterations,

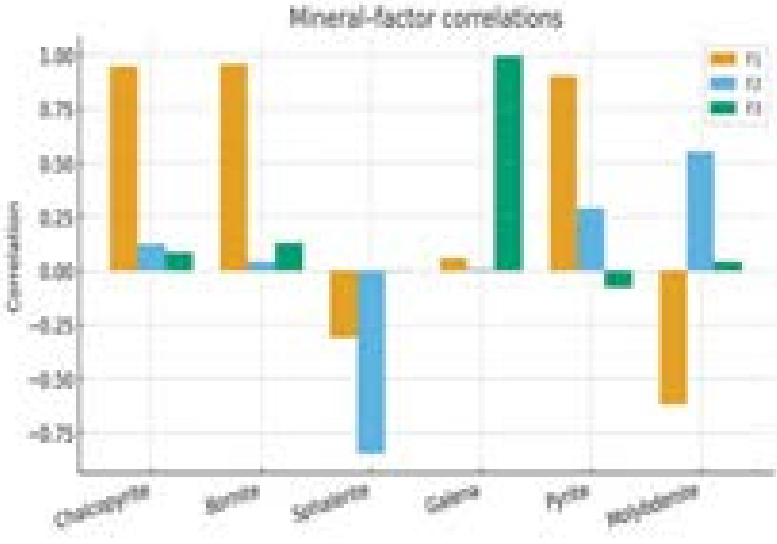


Fig. 6. Mineral–factor correlations

extended argillization and propylitization. Usually, hypogene expanded argillite alteration is formed relatively late in the formation process of the porphyry system [24, 28].

The developed model provides ideas not only about the lateral location of the metasomatic zone and sulphide mineralization in the ore-bearing intrusive, but also about the vertical determination of the

intrusive and mineral association [29], and touching on the proportions of metasomatic zones (from the center to the edges and from the bottom to the top: kalifeldspathization, biotitization, sericitization, propylitization, argillisitization, and silicifivation), it was also stated that most ore- bearing porphyry stocks were formed at a depth of 0.6-4.0 km from the surface.

Formation conditions

Studies of fluid inclusion. Recently, considerable attention has been paid to studies of the influence peculiarities of magmatic systems on ore-forming processes. Fluid inclusion analysis is increasingly used to solve these problems, allowing direct information on the physicochemical parameters of magmatic processes to be obtained. In the case of porphyry copper fields, the study of inclusions in quartz impregnations has provided a significant amount of information on ore-magmatic systems [4, 6, 26].

The use of the thermobaric geochemistry method provides for the establishment of the sequence of fluid inclusion capture in minerals of igneous rocks of ore-magmatic systems and in different mineral associations of fields, reconstruction of such parameters as temperature, salinity, gas content and metal content of fluids responsible for mineralization based on fluid inclusions, and establishing the nature of metal-bearing solutions [12, 31].

Fluid inclusions in ore-associated minerals, including Cu sulfates and quartz, show that the ore-forming fluid may have a mineralization of 2-5 wt% NaCl eq, although there may be a marked increase in mineralization with depth to 20-30 wt% NaCl eq below the ore zone [12]. This spatial separation of the low-mineralized hydrotherms, which are associated with the ores of highly sulphidized fields over the more mineralized hydrotherms in the subsurface of the system, differs from the higher mineralization of the hydrotherms that are located in deeper porphyry copper fields, where hypermineralized brines coexist with low-mineralized steam. This difference may be due to the high density of the brine, which cannot easily rise to shallow depths [5, 31].

The physical and chemical conditions of the formation of fields in the studied area can be judged by gas-fluid inclusions. We have applied the methods of homogenization and decrepitation of inclusions in quartz, galena, sphalerite and chalcopyrite in all successive stages of minerogenesis, which allows to trace the nature of alterations in the temperature regime of solutions in space and time. Fifteen samples from veins and veinlets of fields and ore occurrences of the Murovdag ore district, representing different types of mineral associations, were studied. Three generations of fluid inclusions were distinguished in quartz grains among the studied fluid inclusions according to the known criteria (Redder, 1987): I – primary, located within quartz grains with resistive fractures; II – primary-secondary, not extending beyond the boundaries of quartz grains; III – secondary, associated with resistive fractures. Fluid inclusions, which are uniformly distributed in the volume of the host mineral or confined to growth zones, are classified as primary. Inclusions confined to fractures crossing the host mineral were considered secondary. Primary-secondary fluid inclusions are confined to fractures that do not reach the outer boundaries of crystals and grains, and they are similar to primary inclusions in terms of phase filling [21, 24].

Four quartz-containing rock samples M-3,M-4, M-6 and M-10 were used for the investigation of fluid inclusions. Fluid inclusions in all samples were selected as primary and secondary according to their origin, and transparency and fluid inclusions were determined that allowed to observe the phase changes during microthermometric measurements for measurement. Primary inclusions are two-phase inclusions which are fluid and gas (type SG) at room temperature.

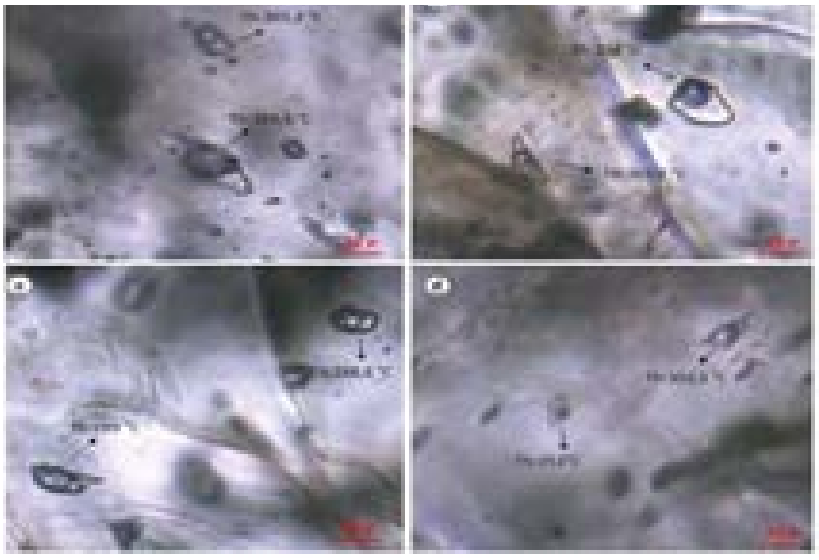


Fig. 7. View of PS-type, primary fluid inclusion associations found in quartz minerals (a, b, c, d)

The fluid phase is larger in volume than the gas phase and dominates in fluid-gas inclusions in quartz mineral. All measured primary fluid-gas type inclusions were homogenized in the gas phase. No measurements were made on secondary inclusions developing along the fractures (Fig. 7).

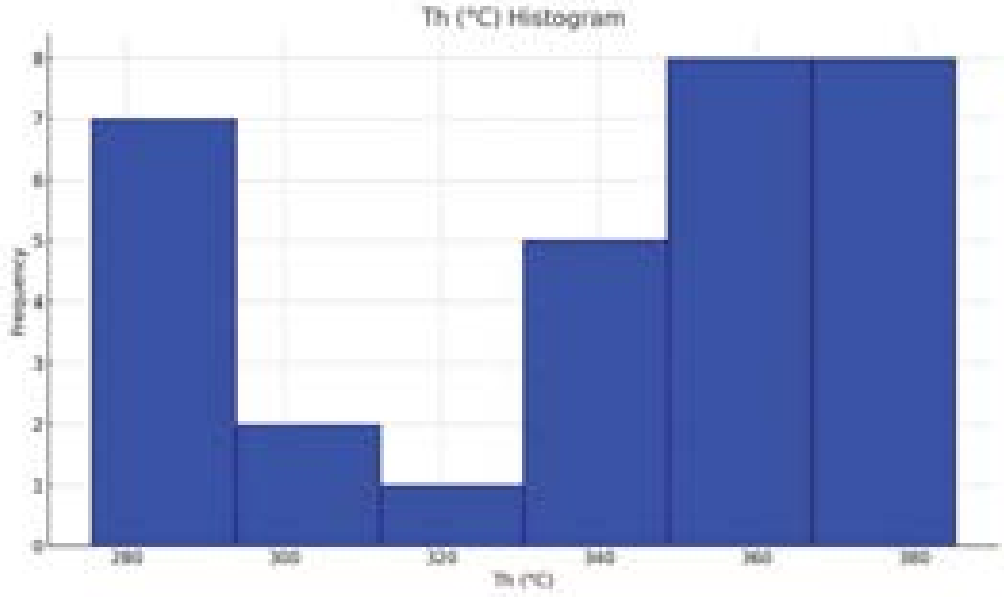


Fig. 8. Frequency histogram of homogenization temperature (Th) obtained on quartz minerals

Size of fluid inclusions found in the studied quartz samples range from 5 to 30 mμ and are typically 15 microns in size. The final melting temperature (Tm °C) and homogenization temperature (Th°C) of fluid inclusions were measured by microthermometric measurements on the studied quartz samples. It was found that Tm is between 1.5-4.8°C in the measurements performed on fluid-gas type inclusions. The homogenization temperatures (Th, °C) of the fluid-gas type inclusions range from 253.3-380°C in microthermometric measurements, and the salinity corresponding to Tm ranges from 2.6% to 7.6% NaCl ([8, 20,21].

The distribution of obtained homogenization temperature (Th) values is reflected in the Th frequency histogram (Fig. 8). The value of homogenization (Th) varies between 250-300°C (on average 278°C Th) among the first group of inclusions, and has an average salinity of 5.2% NaCl-eq. The temperatures of the inclusions in the second group are higher – 350-380°C (on average Th 366°C), and the average salinity varies in 5% NaCl eq. The value of homogenization temperature (Th) obtained from quartz minerals was determined to be 313°C on average [8, 20].

According to the obtained microthermometric data, the initial average salinity of the fluid inclusions in the quartz mineral was 5% NaCl and the temperature was 366°C, and the temperature of the fluid inclusions reached 278 °C on average, and the salinity was 5.2% NaCl on average in the later stages of mineralization (Fig. 9).

To identify the source of ore-forming solutions by the stages of minerogenesis of the Murovdag ore district, data on the isotopic composition of sulfur, sulfides and the gas phase of ore-bearing quartz-pyrite-chalcopyrite and quartz-chalcopyrite hydrotherms were used. A directed fractionation of sulfur isotopes towards enrichment of sulfides with a light isotope from the early productive stage of ore deposition to the late one was established, as a consequence of a natural increase in the oxidation potential of the hydrothermal system. Sulfides, completing the ore process of the quartz-sphalerite-chalcopyrite stage, are characterized by a marked enrichment in the heavy sulfur isotope δS^{34} with a rather narrow range of variation of δS^{34} from +0.1‰ to +0.7‰. A similar value of $\delta^{34}S$ = +10.0‰ was also shown by pyrrhotite from the halo of disseminated sulfide mineralization on the flank of the stockwork. The obtained sulfur isotope data of sulfides (+0.1‰ to +0.7‰) are significantly heavier than the range of values ($\delta^{34}S$ = 0±35‰) attributed to magmatic sulfur [13, 21, 25]. Heavy isotope-enriched sulfur could have been formed by hydrolysis of sulfides contained in the host sedimentary rocks [23]. In this case, there are no characteristic differences in the ratios of sulfur isotopes in pyrite from impregnation in wallrock altered rocks, from veinlets in host rocks and pyrite from the most enriched parts of mineralized zones [20]. So, it is assumed that there was a single source of sulfur in pyrites, which were formed under similar conditions, and the absence of sulfates in direct association with sulfides, relatively homogeneous isotopic composition of pyrite, and finally, the absence of directional separation of isotope during the ore-forming process indicate the homogenization of heavy sulfur under certain high-temperature conditions [21, 25, 26].

Ore-forming hydrothermal solutions, according to the study of fluids at 30 wt.% NaCl eq. Ore components were transported by these solutions in the form of complex ions containing sodium and potassium chlorides, and less frequently sulfates and carbonates. Mineralization occurred in the range of 350-200°C [28].

Since meteoric waters can play a significant role in the formation of porphyry fields, the occurrence of anhydrite can also be associated with the enrichment

of the lower parts of hydrothermal systems with hypergene sulfate ion in accordance with the known hydrochemical zonality of confined groundwater. The relative role of juvenile and surface waters can apparently vary widely, which is reflected in the peculiarities of the geological structure, megasomatic and ore zoning of separate fields [28].

The formation of Goshgarchay field occurred in a narrow temperature range from homogeneous fluids of essentially Na-chloride composition with moderate and low salinity. It is a typical hydrothermal field. The relatively low temperature and pressure of ore-forming fluids at this field, in comparison with other fields in the Murovdag region, may be due to the fact that only one of the four stages of porphyry copper mineralization, which usually occur in other large fields in the region, takes place here.

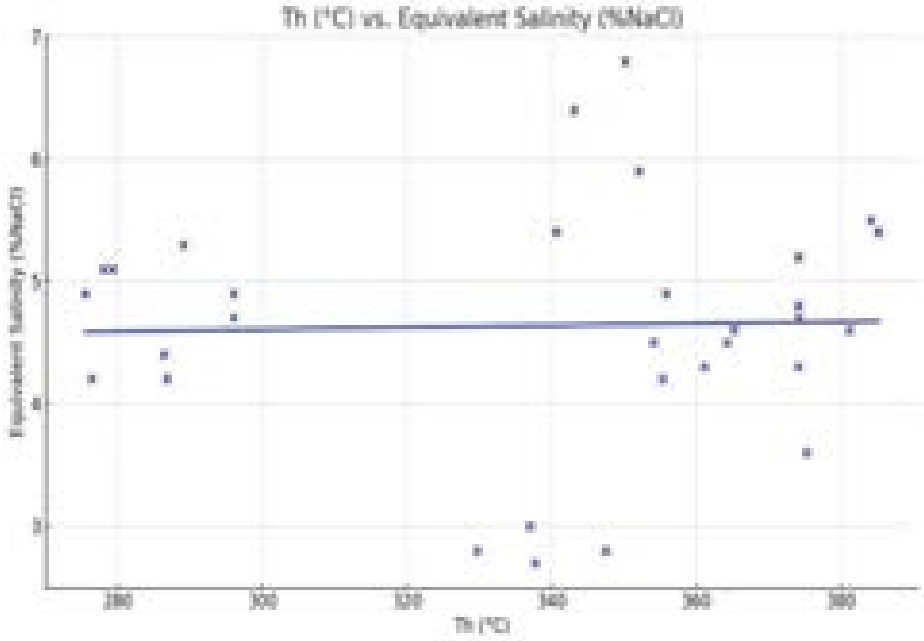


Fig. 9. Equivalent salinity diagram between homogenization temperature and NaCl % obtained on quartz minerals

So, the available data show a magmatic and partially surface origin of the substance of porphyry copper ores and solutions from which they were formed.

In most cases, the porphyry copper ore fields of the studied ore district are characterized by an insignificant level of erosion truncation, which can be judged by the analysis of facies and thicknesses of sedimentary and sedimentary-volcanogenic rocks and their paleotectonic reconstructions, by the facies of the depth of igneous rocks, by the occurrence of low-temperature contact minerals (epidote, zoisite, albite, chlorite, etc.). All this show that only the upper parts of the intrusive massifs and the spatially associated porphyry copper fields have been exposed. The ranges of values of this indicator allow to create a model of the horizontal and vertical section of the Goshgarchay porphyry copper field (Fig. 10, 11). The field is characterized by the upper ore level of

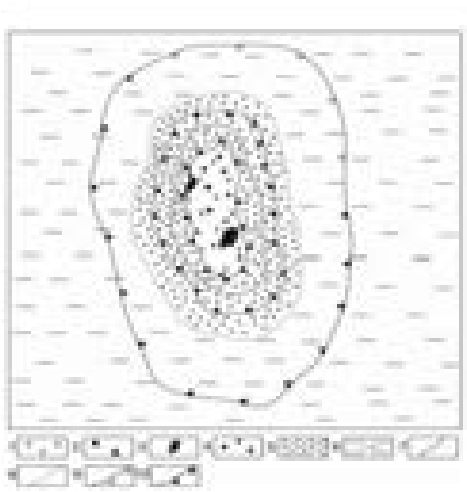


Fig. 10. Model of Goshgarchay porphyry copper deposit in vertical section: 1 - granodiorites; 2 - explosive breccias; 3 - quartz core zone; 4 - presumed kalifeldspathization zone; 5 - silicification, sericitization and chloritization zone; 6 - propylitized rocks; 7 - ore-bearing porphyry intrusive; 8 - intrusive pyritization halos; 9 - industrially significant mineralization boundary; 10 - section line

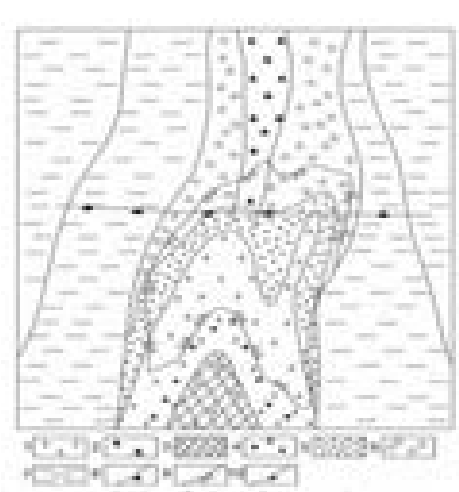


Fig. 11. Model of Goshgarchay porphyry copper mineralization in horizontal section: 1 - ore porphyry intrusive; 2 - breccia pipe; 3 - quartz core; 4 - presumed kalifeldspathization zone; 5 - silicification, sericitization and chloritization zone; 6 - argillization zone; 7 - propylitized rocks of intrusive ledge; 8 - border of intrusive pyritization halos; 9 - border of industrial mineralization; 10 - state of the erosion section

the section, epithermal mineralization is preserved most completely here, and a significant volume of porphyry copper ores is predicted at depth.

The main components of the models are the host frame (phaneric intrusions), small porphyry bodies of stock and dike types (as a rule, localized in the zones of development of ore-controlling structures and spatially closely related to mineralization), breccia bodies, ore bodies and ore-metasomatic zoning [28]. The model takes into account known ideas about the nature of the relationship between mineralization, small porphyry intrusions and locally widespread ore-bearing hydrothermalites [3, 18].

Conclusions

1. The Murovdag ore district is a promising area for porphyry copper, as well as gold and polymetallic ores.

2. Intrusive complexes with porphyry copper mineralization belong to the Late Jurassic-Early Cretaceous gabbro-diorite-granodiorite formation by geological and petrological peculiarities. The characteristic elements of the intrusions are Cu, Pb, Zn, Ag, Mo.

3. The generalized column of metasomatic zoning on the scale of the ore district and field is expressed in the successive change of the following zones: quartz → potassium feldspar → quartz-sericite → argillite → propyllite.

4. Fluid inclusions in minerals associated with the ore, including Cu sulfates and quartz show that the ore-forming fluid may have a mineralization of 2-5 wt.% NaCl eq., although there may be a marked increase in mineralization with depth to 20-30 wt.% NaCl eq. below the ore zone.

5. Hydrothermal ore deposition within the Murovdag ore district occurred in a wide temperature range (350-200°C). Each type of mineralization corresponds to quite a certain range of physicochemical parameters and chemical composition of the ore-forming fluid.

6. Sulfides, which complete the ore process of the quartz-sphalerite-chalcopyrite stage, are characterized by a marked enrichment in the heavy sulfur isotope δS^{34} with a rather narrow range of δS^{34} variation from +0.1‰ to +0.7‰. The obtained sulfur isotope data of sulfides (+0.1‰ to +0.7‰) are significantly heavier than the range of values ($\delta 34S = 0 \pm 35$‰) attributed to magmatic sulfur.

7. Based on mineralogical, geochemical, fluid inclusion and sulfur isotope data, the Goshgarchay porphyry copper field represents a late stage of peripheral magmatic and hydrothermal mineralization, likely underlain by a latent porphyry field.

8. The formation of the Goshgarchay porphyry copper deposit began with the occurrence of primary quartz veins at a depth of 2.5-3 km at a temperature of 400-250°C. Porphyry copper ores were formed in a post-magmatic hydrothermal environment at a depth of about 0.5-1.0 km at a temperature range of 365-200°C.

9. The complexity of the objects shows the high potential of porphyry copper areas and selected areas in the rank of potential ore fields.

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Конфлікт інтересів: автор повідомляє про відсутність конфлікту інтересів

Декларація про використання генеративного штучного інтелекту: автор підтверджує, що під час підготовки рукопису не використовувалися інструменти штучного інтелекту.

Conflict of Interest: The author declare no conflict of interest.

Declaration of use of generative artificial intelligence: The author confirms that no AI tools were used during the preparation of the manuscript.

Геолого-генетичні особливості формування мідно-порфірового зруденіння в Гошгарчайській порфіро-епітермальній системі (Малий Кавказ, Азербайджан)

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АНОТАЦІЯ

Проведено обґрунтування тривалого та багатоетапного формування родовищ ендогенних руд та проявів геологічних та фізико-хімічних умов зруденіння, рудно-метасоматичної та геохімічної зональності в порфіро-епітермальних системах. Досліджено геолого-генетичної характеристики формування мідно-порфірової мінералізації Гошгарчайської порфіро-епітермальної системи за геологічними та фізико-хімічними критеріями. Зразки гірських порід досліджували методом мас-спектроскопії з індуктивно пов'язаною плазмою (ICP-MS) (Туреччина, Ізмір). Аналітичні дослідження проводились в Аналітичній лабораторії Геологічної служби США (USGS, Denver). Ізотопний аналіз проводився в лабораторії стабільних ізотопів Університету Арізони (Thermo Quest Finnigan Delta Plus XL). Дослідження рідинних включень проводилися в лабораторії Стамбульського університету. Основою фактичного матеріалу була колекція проб (близько 150 шт.), відібраних всередині та навколо штокверка з жильно-вкрапленим зруденінням та на його фланзі до глибини понад 500 м від поверхні. Зразки були використані для виготовлення петрографічних тонких зрізів і пластин, відполірованих з обох сторін для дослідження рідинних включень, а решта цих зразків була згрупована та розсіяна на ситах. Характерними елементами інтрузій є Cu, Pb, Zn, Ag, Mo. Флюїдні включення в мінералах, пов'язаних з рудою, включаючи сульфати Cu та кварц, показують, що рудоутворюючий флюїд може мати мінералізацію 2-5 мас.% екв. NaCl, хоча може спостерігатися помітне збільшення мінералізації з глибиною до 20-30 мас.% екв. NaCl. нижче рудної зони. Кожному типу зруденіння відповідає цілком певний діапазон фізико-хімічних показників і хімічного складу рудоутворюючої рідини. Сульфіди, що завершують рудний процес кварц-сфалерит-халькопіритової стадії, характеризуються помітним збагаченням важким ізотопом сірки δS34 з досить вузьким діапазоном зміни δS34 від +0,1‰ до +0,7‰. Мідно-порфірові руди утворилися в постмагматичному гідротермальному середовищі на глибині близько 0,5-1,0 км в діапазоні температур 365-200°C. Виходячи з мінералогічних, геохімічних даних, флюїдних включень і ізотопів сірки, Гошгарчайське порфірове родовище міді представляє пізню стадію периферійної магматичної та гідротермальної мінералізації, яка, ймовірно, лежить в основі прихованого порфірового поля. Формування Гошгарчайського мідно-порфірового родовища почалося із залягання первинних кварцових жил на глибині 2,5-3 км при температурі 400-250°C. Мідно-порфірові руди утворилися в постмагматичному гідротермальному середовищі на глибині близько 0,5-1,0 км в діапазоні температур 365-200°C. Складність об'єктів свідчить про високий потенціал міднопорфірових ділянок і окремих ділянок у ранзі потенційних рудних родовищ.

ІНФОРМАЦІЯ ПРО СТАТТЮ

Рукопис надійшов
18 листопада 2025

Отримано після рецензування
9 лютого 2026

Затверджено до друку
25 травня 2026

Опубліковано онлайн
30 травня 2026

Ключові слова:

Гошгарчайська порфірово-епітермальна, геохімічна, генетична характеристика, рідкісноземельні елементи, гідротермально-метасоматичні зміни, середовище еволюції, генетичні особливості, мідно-порфірове зруденіння, пропілітова зміна.

https://doi.org/10.26565/2410-7360-2026-64-06

УДК 551.7(477.54)(622.426/442)

Стратиграфія юрської системи району села Кам'янка. Частина 4. Кам'янська світа

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АНОТАЦІЯ

Стаття присвячена дослідженню кам'янської світи юрської системи північно-західної околиці Донецької складчастої споруди та є продовженням серії робіт, присвячених стратиграфії юрських відкладів району м. Ізюм та с. Кам'янка. Дослідження набуває особливого значення у зв'язку з тим, що класичні відслонення кам'янської світи, відомі багатими знахідками макрофлори, можуть бути пошкоджені або втрачені внаслідок воєнних дій на території України. Попередні дослідження середньоюрських відкладів України засвідчили наявність багатих макрофлористичних комплексів батського віку. Водночас деякі розрізи та групи комплексів органічних решток залишаються недостатньо вивченими й потребують сучасного перегляду. Дослідження базується на літологічних і палеонтологічних матеріалах з відслонень та свердловин північно-західного Донбасу. Вивчено макрофлору, спори, пилок та супутні палеонтологічні рештки. Встановлено, що кам'янська світа представлена переважно пісковиками, алевролітами, глинами та вугленосними відкладами континентального і прибережного походження. Нижня частина світи є переважно піщаною, верхня – глинистою, з прошарками бурого вугілля, викопної деревини та туфогенного матеріалу. Осадконакопичення відбувалося в алювіальних, дельтових, лагунних та прибережно-морських умовах. Макрофлористичні комплекси включають хвощі (Neocalamites), папороті (Dicksonia, Coniopteris, Eboracia), беннетитові (Ptilophyllum), гінкгові (Ginkgodium), хвойні (Pagiophyllum) та деякі залишки голонасінних рослин невизначеної спорідненості (наприклад, Taeniopteris та коріння). Розсіяні кутикули вказують на присутність різних інших видів голонасінних, включаючи ширший спектр Bennettitales, Ginkgoales та хвойних. Палінологічні комплекси характеризуються переважанням спор Cyathidites, Osmundacidites і Gleicheniidites та пилку Classopollis, Callialasporites, Perinopollenites і Araucariacites. Їх склад свідчить про існування вологих лісових екосистем із поступовим посиленням ролі хвойних рослин. Комплекс літологічних, макрофлористичних і палінологічних даних підтверджує середньо-пізньобатський вік кам'янської світи. Порівняння середньобатських і пізньобатських палінокомплексів свідчить про поступову аридизацію клімату та зміну рослинного покриву від більш вологолюбного до відносно сухішого. Виявлені комплекси добре корелюються з одновіковими відкладами Скандинавії (Сконе) та інших регіонів Європи, що дозволяє використовувати їх для міжрегіональних стратиграфічних зіставлень і палеоекологічних реконструкцій.

ІНФОРМАЦІЯ ПРО СТАТТЮ :

Рукопис надійшов
3 квітня 2026

Отримано після рецензування
20 травня 2026

Затверджено до друку
25 травня 2026

Опубліковано онлайн
30 травня 2026

Ключові слова:

фосилії, палінологія, макрофлора, стратиграфія, юрська система, батські відклади, кам'янська світа, літологія, Північно-Західний Донбас, Україна.

Як цитувати : Матвєєв Андрій, Шевчук Олена, Вайда Віві, Маклафлін Стівен (2026). Стратиграфія юрської системи району села Кам'янка. Частина 4. Кам'янська світа. *Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology*, (64), 78–94. https://doi.org/10.26565/2410-7360-2026-64-06

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Вступ

Ця стаття є продовженням низки публікацій, присвячених стратиграфії юрських відкладів одного з ключових в цьому відношенні районів північно-західного Донбасу – околиць с. Кам'янка та м. Ізюм. Стан проблеми та аналіз попередніх робіт приведені нами у першій статті [5].

Кам'янська світа широко відома в науковій літературі завдяки дослідженню багатої середньоюрської флори, яку вона містить. Накопичення відкладів відбувалось в умовах досить великої річкової дельти протягом пізнього бату. Нажаль, лісовідновлювальні роботи 1960-х років призвели до майже повного знищення класичних природних відслонень світи. Наразі вона представлена фрагментарно, у вигляді невеликих виходів та за результатами буріння.

Слід зазначити, що сучасний стан вивченості кам'янської світи суттєво ускладнений внаслідок військових дій, що тривають на території України з 2022 року. Частина відслонень опинилася в зоні обмеженого доступу або зазнала порушення, що значно ускладнює проведення польових досліджень та повторне вивчення розрізів [8, 19]. У зв'язку з цим особливого значення набуває узагальнення раніше отриманих матеріалів у поєднанні з новими лабораторними дослідженнями.

Аналіз попередніх публікацій. Відклади континентальної середньої юри північно-західного Донбасу мають досить тривалу історію дослідження. Перша праця, в якій приводяться дані про їх дослідження, належить Г. Бледе (1840) в якій вони, були спочатку віднесені до кам'яновугільної системи. Втім, вже у 1841 році, той же дослідник вказує їх лейасовий вік. В подальшому опис відслонень та визначення віку цих відкладів, а також опис окремих залишків рослин, приведено в працях І.Ф. Леваковського (1862, 1873) та О.В. Гурова (1869, 1882, 1893). Систематичні дослідження відкладів кам'янської світи пов'язані з геологічним картуванням, яке проводилось наприкінці XIX — початку XX сторіч. В цей час систематизовано опис всіх відслонень (Борисяк, 1905) та проведено перше монографічне дослідження кам'янської флори (Томас, 1911) [1, 17].

Наступний етап дослідження світи припадає на роботи з геологічного картування середини XX сторіччя. В цей час додаються матеріали по складу рослинних решток (Станіславський (1953, 1957); Вахрамеєва (1964, 1990)), фаціям та палеогеографії (Канський, Макрідін (1956)), стратиграфії (Мігачова, Стерлін (1954), Макрідін, Мігачова, Стерлін (1961), Ямніченко (1961, 1962), Станіславський, (1964)) [1].

Окремі аспекти палінологічної характеристики відкладів кам'янської світи вже були предметом спеціалізованих досліджень, результати яких опубліковані раніше [20]. Втім, ці роботи мали обмежений обсяг вибірки та були зосереджені переважно на розрізах поблизу с. Кам'янка. У даній статті здійснено узагальнення наявних матеріалів із залученням нових зразків та розширенням стратиграфічного охоплення, що дозволяє уточнити склад спорово-пилкових комплексів та їх стратиграфічне значення.

Матеріал та методи

В районі с. Кам'янка кам'янська світа поширена досить широко, але наразі показових відслонень не має. Найбільш багаті збори макрофлори зроблені під час будівництва доріг, ці відслонення зараз недоступні.

Класичні відслонення кам'янської світи розташовані в ярах на північ від с. Кам'янка (Рис. 1), найповніше з них знаходиться в вузькому ярі, який тягнеться на схід від дороги Ізюм – Слов'янськ майже паралельно їй.

Нижня піскувата частина світи відслонюється в низці ярів правого борту балки Суха Кам'янка. Там же знаходиться Сухокам'янське родовище бурого вугілля, розвідане в 1939 році, результати якого нами також використані.

Верхня глиниста частина світи відслонюється в правому березі р. Сіверський Донець поблизу колишнього хутора Шевченки.

Нами були проаналізовані дані, отримані під час картувальних та пошукових робіт різного масштабу, які проводились в районі с. Кам'янка, а також узагальнені відомості з власних зборів та літературних даних про знахідки викопних решток.

Також, проведено мацерацію досліджених порід в лабораторії Інституту геологічних наук НАН України за стандартною методикою первинної обробки зразків на палінологічний аналіз та частина зразків було оброблено відповідно до стандартних палінологічних процедур у Global Geolab Limited. Палінологічні дослідження проводились із використанням стандартизованих методик підготовки зразків, включаючи кислотну мацерацію, просіювання та мікроскопічний аналіз органічних залишків. Для частини матеріалу було виконано кількісний підрахунок паліноморф із визначенням їх відносного вмісту. Отримані результати співставлялись із раніше опублікованими даними по юрських відкладах Дніпровсько-Донецької западини, що дозволило забезпечити регіональну кореляцію палінологічних комплексів [5-7, 19-21].

Палінологічні зразки зберігаються у відділі стратиграфії та палеонтології мезозойських відкладів Інституту геологічних наук Наці-

ональної академії наук, Київ; макрофлора – Харківському музеї природи, Харків.

Результати та обговорення

Кам'янська світа виділена Л.Ф. Лунгенрсгаузеном у 1941 році. Стратотип вказаний не був, але оскільки майже всі дослідження світи до середини XX сторіччя проводились в системі великих ярів на північ від с. Кам'янка, можна припустити, що стратотиповий розріз розташований саме тут. Втім, наразі ці відслонення майже повністю штучно терасовані та задерновані, а виходи світи на поверхню фрагментарні. Всі існуючи відслонення світи в районі с. Кам'янка показані на рисунку 1, втім, жодне з них не відображає більш менш повного її обсягу та не може бути запропоновані в якості еталону. Найбільш повно світа відслонюється в низці ярів в правому борті балки Суха Кам'янка в 3,5 кілометра на південний-схід від кам'янських відслонень.

Літологія. За літологічним складом кам'янська світа поділяється на дві нерівні частини: нижню — складену пісковиками та верхню — глинисту.

Нижня частина складена пісковиками дрібно та середньозернистими жовтувато-сірими та зеленувато сірими, переважно слабозцементованими, але з окремими міцнозцементованими прошарками. Пісковики шаруваті з горизонтальною та косою шаруватістю. В нижній частині пісковики перешаровуються з глинами та глинистими пісковиками. В складі пісковиків присутня певна домішка пірокластичного матеріалу [13], який при вивітрюванні надає пісковиками жовтого кольору. Залишки рослинності в цій частині світи досить рідкі, зазвичай концентруються в глинистих та вуглисто-глинистих тонких прошарках та лінзах. Зустрічаються відносно невеликі (до 30 см) уламки зкрем'янілої деревини. Потужність товщі пісковиків досягає 80-90 м.

Верхня частина складена глинами досить строкатими як по складу - від чистих глин до піскуватих глин, так і за кольором — зеленувато-сірі, сірі, жовто-сірі, жовто-червоні, чорні. Склад глин швидко міняється як по розрізу, так і по латералі. По свідченням дослідників важко або неможливо співставити розріз глин, які відслонюються навіть в сусідніх ярах.

За мінералогічним складом глини каолінит-гідрослюдисті. Важка фракція алевритів містить біотит, циркон, турмалін, гранат, епідот, дістен, рогову обманку та брукіт. В товщі глин зустрічаються прошарки та лінзи пісковиків, іноді грубозернистих до гравелітів. Зазвичай в таких лінзах містяться великі (окремі стовбури до 0,5 м діаметром та до одного метру довжиною) уламки вуглефікованої деревини, часто піритизованої, іноді в прижиттєвому положені. Окрім того, часто пісковики зцементовані лімонітом та переходять в бурий залізняк. Також у глинах, особливо в їхній верхній частині, зустрічаються прошарки та лінзи вуглистих глин, бурого вугілля та окремі уламки та скупчення вуглефікованої деревини. Загальна потужність глин досягає 30-40 м.

Вугленосність кам'янської світи відмічалась багатьма дослідниками, втім, ніяких конкретних даних не наводилось. Залишки буровугіль-

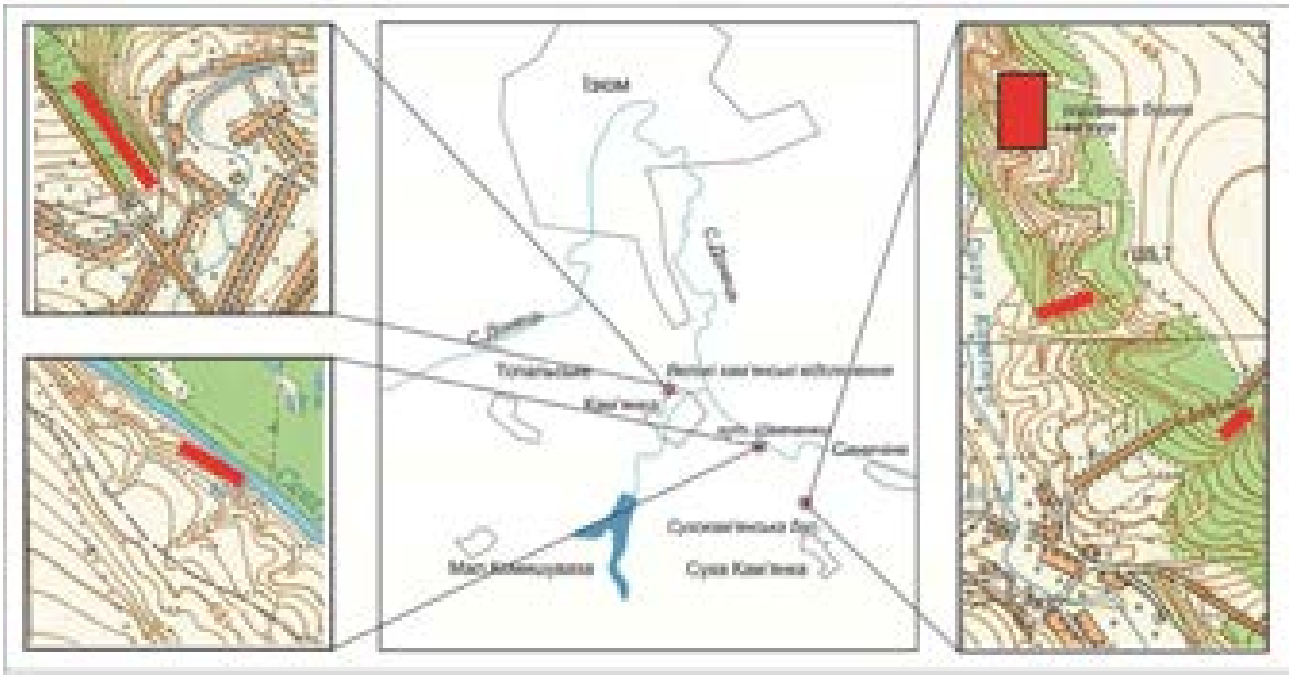


Рис. 1. Схема розміщення досліджених розрізів
Fig. 1. Scheme of placement of the investigated sections

ної деревини розсіяні в верхній – глинистій – частині світи. Зазвичай це поодинокі, досить великі уламки деревини або невеликі лінзи бурого вугілля. В 1939 році на правому борті балки Суха Кам'янка в одному кілометрі північніше однойменного села було розвідано невелике родовище бурого вугілля.

Розвідувальними виробками (свердловинами, канавами та штольнями) було вскрито три пласта вугілля та один пласт вугільної глини. Пласти мають дуже мінливу потужність від 0,1 до 0,6 м, з частими незакономірними пережимами та виклинюванням. Якість вугілля по простяганню також сильно мінлива. Теплотворна здатність вугілля міняється від 1500 до 4900 ккал/кг, також міняється вміст глини та піску. При проходженні штолен також відмічалась досить різка зміна вміщуючих порід: переважно різноманітних глин, але також і пісковиків.

Родовище промислового значення не має, втім розкриває особливості будови верхньої частини кам'янської світи та умови палеогеографії пізньокам'янського часу.

В деяких розрізах в районі с. Кам'янка на флороносних глинах залягають світло-сірі каолинисті крупнозернисті піски з косою верствуватістю річкового типу невеликої потужності до 5-10 м. В пісках, особливо в їх нижній частині зустрічаються лінзи пісковиків, гальки та бурого вугілля. Вік їх палеонтологічно не підтверджений. Умовно їх відносять до нижнього келовею та виділяють в окрему *Товщу білястих пісків та пісковиків*. На наш погляд, ця товща є складовою кам'янської світи та відповідає русловій фації алювіальних відкладів пізньокам'янського часу.

Палеонтологічні рештки. *Рослинні рештки.* Перші описи макрофлори з юрських відкладів району с. Кам'янка належать Е.І. Ейхвальду (1875). Пізніше описи окремих видів проведені А.В. Гуровим (1982). Перша, узагальнююча робота з описами юрських рослин, але без їх зображень належить Н.В. Гигор'еву (1900). Перша повноцінна монографія вийшла у 1911 році під авторством Х. Томаса. Саме після цієї монографії в геологічну літературу комплекс середньоюрської флори північно-західного Донбасу ввійшов під назвою "кам'янська флора" [1]. Нарешті у 1957 році результати спеціальних розшуків та дослідження Ф.А. Станіславського були монографічно опрацьовані [9-11] та описані 70 видів рослин.

За результатами дослідження було встановлено, що в складі флористичного комплексу найбільш представлені папороті та цикадофіти, також представлені хвощі, гінгкові та хвойні. В комплексі присутні двадцять два види папоротей, п'ять хвощів, двадцять видів цикадофіт, чотирнадцять видів хвойних. Загалом, на думку Ф.А. Станіславського, флора має типовий середньоюрський вигляд, але містить деякі більш давні релікти. Типові форми збереженості макрофлори з кам'янської світи приведені на рис. 2.

Спори та пилок вищих рослин. Палінологічний комплекс кам'янської світи характеризується значним таксономічним різноманіттям і включає спори вищих спорових рослин, пилок голонасінних, а також поодинокі представники інших груп органічних мікрофосилій.

Нами детально вивчено середньоюрські відклади з серії відслонень північно-західного Донбасу і встановлено два спорово-пилкових комплекси: середньо- та пізньобатський, що відповідають відповідно двом підсвітам нижній і верхній кам'янської світи.

В ***середньобатському спорово-пилковому*** комплексі спори переважають над пилком голонасінних рослин. Спори зазвичай становлять до 60% від загальної кількості мікрофосилій (Рис. 3-5). Серед спор домінують представники циатейних родів *Coniopteris* sp., *Cyathidites* sp., *Cyathidites australis* Couper, осмундових *Osmundacidites* sp., *O. wellmanii* Coup., *O. nicanicus* (Verb.) Schug., *O. jurassicus* (K.-M.) Kuz.), маратієвих *Marattisporites scabratus* Coup. та трохи менше *Cyathidites punctatiformis* Rom., *C. minor* Coup., *Concavisporites* spp., *C. jurienensis* Balme, *C. junctum* (K.-M.) Sem.), *Cibotium corniculatum* Bolch. Зустрічається невелика кількість глейхенієвих: *Gleicheniidites* spp., *G. laetus* (Bolch.) Bolch., *Plicifera delicata* (Bolch.) Bolch., *Ornamentifera* sp., *O. tuberculata* Bolch. та *Leiotriletes* spp. Встановлено умовний вид-індекс для цього часу *Clathropteris obovata* var. *magna* Tur.-Ket. Постійно присутні і характерні для середньоюрських палінокомплексів *Polypodisporites jurassicus* Iljina, *Todisporites* sp., *T. major* Coup., *T. minor* Coup., *Tripartina variabilis* Maljavkina, *Camptotriletes cerebriformis* Naum. ex Jarosh., *C. rugulatus* Thoms. and Pflug., *Duplexisporites scanicus* (Nilsson) Playford & Dett., *D. amplectiformis* (Kara-Murza) Playford & Dett. *Striatella seebergensis* Mädler, *Coptospora* sp., *Calamospora* sp., *Biretisporites* sp., *Dictyophillidites* sp., *Hymenophyllum* sp., *Chomotriletes anagrammensis* (K.-M.) Prosv., *Acanthotriletes tomiensis* Iljina. Зустрічаються спори плавуноподібних *Leptolepidites* sp., *Klukisporites variegatus* Coup. Відмічено спори водних папоротів *Salvinia* sp. Спори плавунів складають 3,2%, осмундових 8,9%, сфагнових мохів 1,7% *Stereisporites* sp. Пилок голонасінних становить 40% від загальної кількості мікрофосилій (Рис. 6-8). Серед одноборозного пилку переважає Cupressaceae, Ginkgocycadales та *Inaperturopollenites* sp. Постійним є пилок *Taxodiaceapollenites* sp., *Perinopollenites elatoides* Coup., *Cerebropollenites mesozoicus* Nilsson, *Eucomiidites* sp., *Callialasporites* sp., *C. trilobatus* (Balme) Dev., *Eucomiidites troedssonii* (Erdtmann) Potonie, *Chasmatosporites* sp. *Classopollis* sp., *C. classoides* Pflug, *C. chateaunovi*

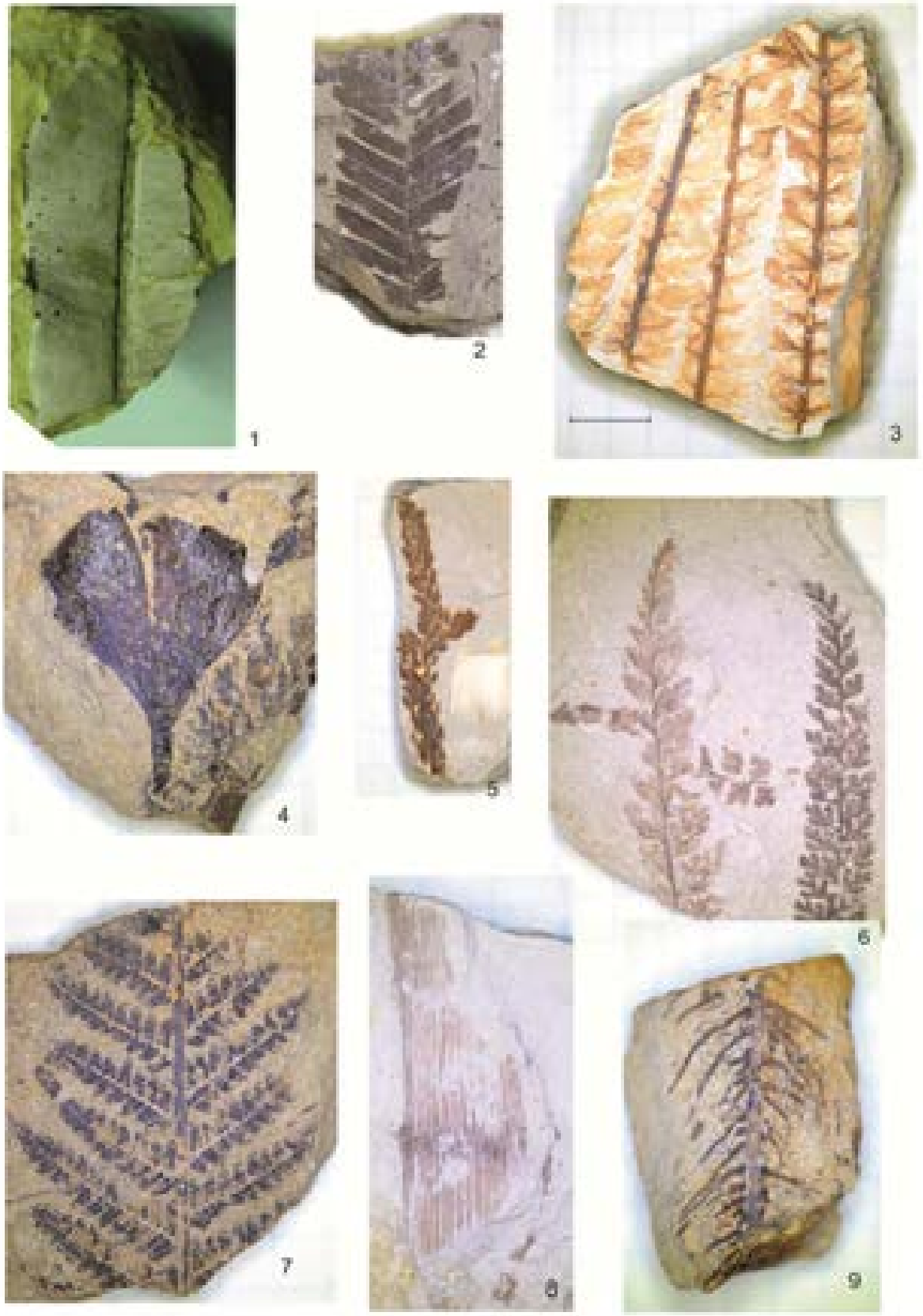


Рис. 2. Типова макрофлора з кам'янської світи (фото авторів). Шкала – 10 мм /
Fig. 2. Typical macroflora from the Kamianska Formation. Scale – 10 mm.
1. *Taeniopteris* sp. cf. *T. vittata* Brongn. Heer. **2.** *Ptilophyllum pecten* (Phill.). **3.** cf. *Dicksonia kendalli* Harris. **4.** *Ginkgodium nathorstii* Yok. **5.** *Pagiophyllum maculosum* Kendall. **6.** *Coniopteris bella* Harris. **7.** *Eboracia lobifolia* (Phillips). **8.** *Neocalamites* sp. Стовбур хвоща. **9.** Неідентифіковане коріння голонасінних рослин (Unidentified gymnosperm roots).

Reyre*, Corollina meyeriana* (Klaus) Venkatachala and Goczan*, Brachyphullum* sp., *Araucariacites* sp., *Araucariacites australis* Cookson., *Bennettites* sp. Пилок хвойних представлений представниками родини Pinaceae, Podocarpaceae, Caytoniaceae, а саме *Piceapollenites* sp., *Picea exilioides* Bolch., *P. singularae* Bolch., *Podocarpidites* sp., *Vitreisporites pallidus* (Reissinger) NIlsson; Srivastava, *Vitreisporites* spp., *Quadraeculina* spp., та їх прадавніми екземплярами *Pseudopiceae magnifica* Bolch., *Protopinus* sp., *Protopinus vastus* Bolch. *Трахеїди:* встановлено фрагменти деревини, що складаються з трахеїд з супротивною пористістю, зі змішаним типом пористості, з облямованими порами араукароїдного типу, з діагональною пористістю. Більший відсоток складають трахеїди *Taxopitus* sp. [15]. *Кутикули:* відмічаються рослинні рештки гінкгових і цикадових у великій кількості. Більшість кутикул адаксіальних, ділянок верхнього епідерміса листка [14]. *Рештки грибів:* визначені спори та гіфи мікроскопічних грибів. *Зелені водорості (празинофіти):* відмічаються поодинокі *Tasmanites* sp.

Характерною рисою ***пізньобатського спорово-пилкового комплексу*** є високий вміст спор *Coniopteris* sp. як і в палінокомплексах середнього бату. Серед спор домінують представники циатейних родів *Cyathidites* sp., *C. australis* Coup*., C. triangularis* (Rom.), *Concavisporites junctum* (K.-M.) Sem., *Alsophila* sp. і трилетні спор групи *Leiotriletes*. Але відмінністю пізньобатських палінокомплексів в цьому розрізі є трохи менша кількість осмундових *Osmundacidites sp., O. densiornamentatus* (Klimko) Zhang*., O. cingulatus* E. Semenova*, O. nicanicus* (Verb.) Schug. Крім того, вперше зустрінуті *Carnisporites granulatus* E. Schulz., *Stoverisporites microverrucatus* Burger., більше екземплярів *Neoraistrickia rotundiformis* (K.-M.) Taras., *Tripartina variabilis* Mal, поодинокі *Camptotriletes cerebriformis* Naum. ex Jarosch., *Duplexisporites anogrammensis* (K.-M.) Schug., *Foraminisporis wonthaggiensis* (Cook. and Dett.) Dett. Зустрічаються спори плавунів – *Lycopodiumsporites* sp., *L. marginatus* Singh., *L. austroclavatidites* (Cookson) Potonie і *Selaginella* spp., *Leptolepidites* sp., *Klukisporites* sp., *K. variegatus* Couper. Характерними для юрського часу в цьому розрізі є *Marattisporites* sp., *Dictyophillidites* sp., *Clathropteris obovata* var. *magna* Tur.-Ket., *Callialasporites trilobatus* (Balme) Dev., *C. dampieri* (Balme) Dev. and *C. segmentatus* (Balme) Srivastava, *Staplinisporites caminus* (Balme) Pocock*, Todisporites major* Coup., *Peromonolites bowenii* Coup. Стає більшим різноманіття сфагнових мохів *Stereisporites* sp., *S. compactus* (Bolch.) Iljina, *S. antiquasporites* (Willson and Webster) Dettmann, *S. glabellus* (Verb.) Sem., *Densoisporites velatus* Weyland and Krieger, *D. psilatus* (de Jersey) Raine and de Jersey. В ідмічаються поодинокі спори *Foveosporites* sp., *Matoniasporites* sp., *Biretisporites* sp. Спор глейхенієвих стає більше, з'являються види глейхенієвих *Gleicheniidites angulatus* (Naum.) Bolch*., Plicifera delicata* (Bolch.) Bolch. та продовжують зустрічатись *Gleicheniidites laetus* (Bolch.) Bolch*., G. senonicus* Ross., *Ornamentifera* sp. і ін. Керівними є з папороттєвих *Coniopteris divericata* K.-M., з плаунів *Selaginella obscura* Bolch, *Leptolepidites verrucatus* Coup. Відмічаються водні папороті *Salvinia* sp. (Рис. 3-5). У пізньобатському палінокомплексі кількість пилку *Classopollis* (*Classopollis* cf. *classoides* Pflug emend. Pococket Jansonius, *C. monostriatus* Zhang, *C. simplex* (Danze-Corsin and Laveine) Reiser & Williams, *C. obidosensis* Groot and Groot, *C. torosus* (Reissinger) Balme, *C. meyeriana* (Klaus 1960) de Jersey, *C. chateaunovi* Reyre) тільки трохи збільшується в порівнянні з середньобатським. Зустрічаються пилкові зерна *Eucomiidites troedssonii* Erdtm. та *Quadraeculina* spp. Невеликій вміст *Bennettites* sp., *Chasmatosporites* sp., *Cerebropollenites mesozoicus* Nilsson, *C. macroverrucosus* Schulz. Переважає безмішковий пилок *Inaperturopollenites* sp., *Perinopollenites elatoides* Coup. та родин Araucariaceae (*Araucariacites australis* Cookson), Cupressaceae, Ginkgocycadaceae та поодинокі *Phyllocladidites bibulbus* (Bo1ch.) Chlonova. Поодинокі *Spheripollenites* sp., *Exesipollenites tumulus* Balme, *Equisetites variabilis* Vin. Також у пізньобатському комплексі стає більшим вміст пилку хвойних родини Pinaceae - *Picea exilioides* Bolch., *Pseudopiceae magnifica* Bolch., *Pinuspollenites* spp., *Alisporites australis* de Jersey., *A. grandis* (Cookson) Dettmann та Podocarpaceae. Поодинокі *Dipterella oblatinoides* Mal., *Chordasporites australiensis* de Jersey. (рис. 6-8). *Трахеїди.* Встановлено фрагменти деревини, що складаються в основному зі східчастих трахеїд, трохи менше трахеїд араукароїдного та змішаного типу. Більший відсоток складають трахеїди *Cupressinoxylon* sp. [15]. *Кутикули.* Відмічаються рослинні рештки гінкгових і цикадових у великій кількості. Більшість кутикул адаксіальних, ділянок верхнього епідерміса листка. Встановлені *Nilssoniopteris taeniata* Samys. Також зустрічаються частини листка з жилкуванням [14]. *Акритархи:* встановлені *Veryhachium* sp. *Зелені водорості (празинофіти): Tasmanites* sp., *Ovoidites* sp. та *Schizosporis reticulatus* Cookson and Dettmann emend. Pierce. *Зелені водорості:* відмічені поодинокі *Botryococcus* sp. *Рештки грибів:* визначені спори та гіфи мікроскопічних грибів з класу фікоміцетів (*Rhizophagites*), конідій

(*Fractisporonites* sp.). Відмічаються поодинокі частини тіла комах. Комплексне вивчення мікрофосилій з батських відкладів північно-західної окраїни Донбасу забезпечило більш точне датування цих відкладів, а саме уточнено вік батської вугленосної товщі північно-західної окраїни Донбасу.

Вік світи – середній-пізній бат, обґрунтований рослинними рештками, стратиграфічним положенням в розрізі та підтверджений спорово-пилковими даними [16-17].

Ілюстративний матеріал представлений розширеним набором фототаблиць паліноморф, що дозволяє більш детально охарактеризувати морфологічні особливості встановлених таксонів (рис. 3-9).

Виявлені батські палінологічні комплекси добре корелюються з одновіковими Європи. Наприклад, дуже подібні до зони Callialasporites – Perinopollenites, що встановлена в скандинавських розрізах [18] і ін. Це свідчить про подібність рослинного покриву на значних територіях та відсутність вираженої провінційності флори в цей час [22-24].

Отримані результати підтверджують батський вік відкладів кам'янської світи та узгоджуються з даними макрофлори [11].

Молюски. В нижній частині світи в туфогенних пісковиках виявлені рештки молюсків: Meleagrinella doneziana (Boriis.), Gocoma (?) carinata Goldf., Ferganoconcha schabarovi Tchern., F. sibirica Tchern. [12], втім, в літературі є тільки списки цієї фауни, монографічно оброблені вони не були.

Стратиграфія. Кам'янська світа була виділена Л.Ф. Лунгерсгаузеном у 1941 році, але стратотип вказаний не був, а назву світи було переокуповано. Ще у 1897 році у середньому карбоні Донбасу співробітниками Геологічного комітету була виділена, а в 1913 р. Л.І. Лутугіним та П.І. Степановим названа кам'янська світа.

Оскільки зараз найкращі відслонення середньоюрських відкладів, що містять макрофлору та підтверджені даними спорово-пилкового аналізу, знаходяться в ярах правого борту балки Суха Кам'янка, ми пропонуємо змінити назву світи з "кам'янська" на "сухокам'янська". Після публікування цих матеріалів буде подана заява до мезозойської комісії Національного стратиграфічного комітету України з пропозицією внесення змін.

Щодо віку утворення кам'янської світи існує два погляди. Дослідники: М.В. Григорьев, Г. Томас, Ф.А. Станіславський [10, 11] вважали, що відклади світи сформувались протягом пізнього бату. Інші: О.О. Борисяк, Б.П. Стерлін, В.П. Макрідін, Є.Є. Мігачова [2, 12] відносили нижньокам'янську підсвіту до пізнього бату, верхньокам'янську – до нижнього келовею.

За нашими даними кам'янська світа в повному обсязі утворилась впродовж середнього-пізнього бату, лише крупнозернисті руслові піски, які залягають в покрівлі світи, можливо мають ранньокеловейський вік.

За літологічними ознаками кам'янська світа впевнено поділяється на дві підсвіти: нижню — піскувату та верхню — переважно глинисту. Загальна потужність кам'янської світи в межах кам'янського полігону складає 120 м. На території північно-західної окраїни Донбасу кам'янська світа підстиляється підлужною світою, а перекривається ізюмською світою.

Порівняльний аналіз середньобатського та пізньобатського спорово-пилкових комплексів розрізу с. Кам'янка демонструє як загальні риси, так і низку принципових відмінностей у таксономічному складі, кількісному співвідношенні груп та появі/зникненні окремих стратиграфічно значущих таксонів.

У середньобатському комплексі спори домінують — до 60%, пилок голонасінних складає близько 40%. Середньобатський палінокомплекс характеризується домінуванням спор (*Cyathidites*, *Osmundacidites*, *Deltoidospora*) при відносно стабільному складі пилку.

У пізньобатському комплексі співвідношення вирівнюється за рахунок зростання пилку голонасінних (особливо Pinaceae, Podocarpaceae) та незначного зменшення ролі окремих груп спор. Пізньобатський комплекс відрізняється зменшенням ролі осмундових, зростанням різноманіття глейхенієвих і сфагнових, появою нових таксонів (*Carnisporites*, *Stoverisporites*, *Staplinisporites*), розширенням спектру пилку хвойних (*Pinaceae*, *Podocarpaceae*), незначною участю мікрофітопланктону.

Тому, пізній бат характеризується тенденцією до зростання ролі пилку, але без різкої зміни структури комплексу (на відміну від келовею). Сукупність цих ознак дозволяє чітко розмежувати середньо- та пізньобатські палінокомплекси та підтверджує вік кам'янської світи як середній-пізній бат.

Умови накопичення. Кам'янська світа завершує середньоюрську трансгресію та відповідає регресійному підциклу. Початок трансгресії припадав на пізньочеркаський час. Завершення трансгресії в кам'янський час супроводжується збільшенням надходження уламкового матеріалу, формуванням дельтових відкладів, поступовим заповненням морського басейну та завершенням накопичення в субаеральних умовах.

В екологічному відношенні флора нижньо та верхньокам'янської підсвіт дещо відрізняється. У флорі нижньокам'янської підсвіти переважають вологолюбиві хвощі, в той час як для верхньокам'янської підсвіти характерна перевага хвойних рослин. Це вказує на аридизацію клімату під час відкладення кам'янської світи.

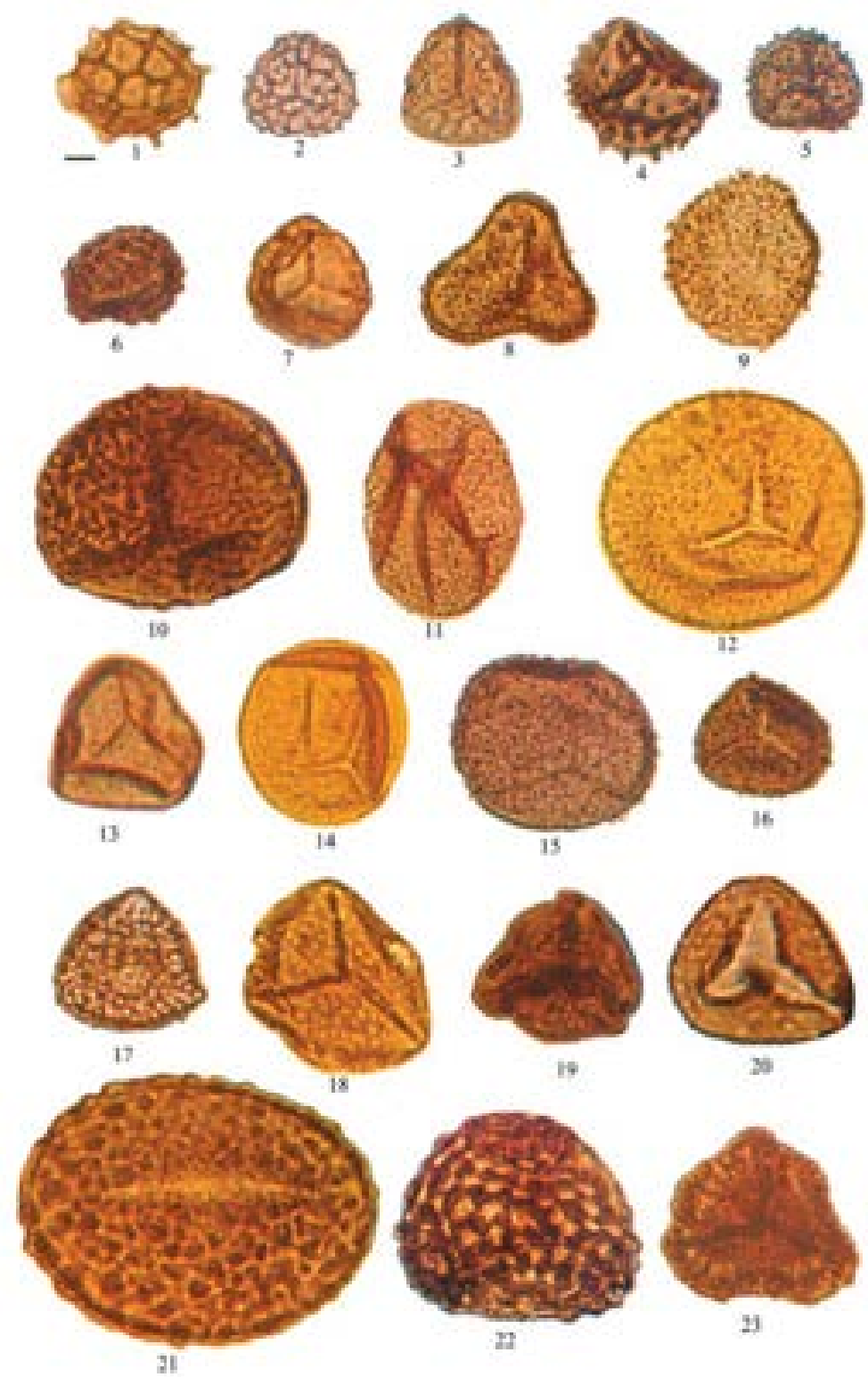


Рис. 3. Спори лікоподієвих та папоротеподібних з відкладів кам'янської світи північно-західної окраїни Донбасу. Шкала – 10 мікрон /

Fig. 3. Spores of lycopods and ferns from the deposits of the Kamianska Formation of the northwestern outskirts of Donbas. Scale bar – 10 microns.

1. *Lycopodiumsporites austroclavatidites* (Cookson) Potonie зр. 1a(1). **2.** *Lycopodiumsporites* sp., зр. 1a(1). **3**. *Retitriletes semimuris* (Danze-Corsin & Laveine) McKellar, зр. 1a(1). **4**. *Neoraistrickia truncata* (Cookson) Pot., зр. 2a(2). **5**. *Neoraistrickia rotundiformis* (K.-M.) Taras., зр. 5a(2). **6.** *Leptolepidites major* Couper, зр. 1b(1). **7**. *Selaginellidites sp.,* зр. 1a(1). **8**. *Anapiculatisporites concinnus* Playford, зр. 3(2). **9.** *Apiculatisporites* sp., зр. 0(1). **10**. *Camptotriletes cerebriformis* Naum. ex Jarosh., зр. 0(1). **11.** *Osmundacidites wellmanii* Coup., зр. 5a(1). **12**. *Osmundacidites fissus* (Leschik) Playford, зр. 3(2). **13**. *Osmunda papillata* Bolch., зр. 5a(2). **14**. *Osmundacidites cingulatus* Sem., зр. 5a(1). **15.** *Osmundacidites wellmanii* Coup., зр. 0(1). **16.** *Osmundacidites jurassicus* Coup., зр. 0(1). **17**. *Microreticulatisporites* sp., зр.0(1). **18.** *Foveosporites pseudoalveolatus* (Coup.) M.Voronova, зр. 3 (1). **19**. *Foveosporites* sp., зр. 2a(2). **20.** *Ophioglossum* sp., зр. 2a(1). **21**. *Peromonolites bowenii* Coup., sp., зр. 2a(2). **22**. *Klukisporites variegatus* Coup., 3(kerogen). **23.** *Uvaesporites* sp., зр. 0(2).



Рис. 4. Спори мохоподібних, хвощеподібних та папоротеподібних з відкладів кам'янської світи північно-західної окраїни Донбасу. Шкала – 10 мікрон /

Fig. 4. Spores of bryophytes, horsetails, and ferns from the deposits of the Kamianska Formation of the northwestern outskirts of Donbas. Scale bar – 10 microns.

1. *Sphagnumsporites antiquasporites* (Wils. and Webs.) Poc., зр. 0(2). **2**. *Stereisporites(Rogalskaesporites) bujargiensis* (Bolch.) E.Schulz, зр. 3(kerogen). **3**. *Cheiropleria congregata* Bolch. (=*Sphagnumsporites* sp.), зр. 2 (kerogen). **4**. *Stereisporites psilatus* (Ross) Pflug., зр. 2а(2). **5**. *Sphagnumsporites* sp. (= *Stereisporites glabellus* (Verb.) Sem.), зр. 1в(1). **6**. *Todisporites major* Coup., зр. 0(1). **7**. *Todisporites minor* Coup., зр. 1а(1). **8**. *Densoisposporites velatus* Weyl. and Krieg., зр.2(2). **9**. *Densoisporites psilatus* (de Jersey) Raine and de Jersey, зр. 3а(2). **10**. *Stoverisporites microverrucatus* Burger., зр. 1а(1). **11**. *Granulatisporites gracilis* Sem., зр. 0(2). **12**. *Carnisporites granulatus* E. Schulz., зр. 1а(1). **13**. *Foraminisporis wonthaggiensis* (Cook. and Dett.) Dett., зр. 2а(1). **14**. *Calamospora* sp., зр. 5а(2). **15**. *Duplexisporites amplectiformis* (Kara-Murza) Playford & Dettmann, зр.3(2). **16**. *Duplexisporites scanicus* (Nilsson) Playford & Dettmann, зр.3(2). **17**. *Camptotriletes* sp., зр. 5а(1). **18**. *Cingutriletes* sp., зр. 3(2). **19**. *Striatella seebergensis* Mädler, зр. 0(1). **20**. *Tripartina variabilis* Mal., 5а (kerogen). **21**. *Dennstaedtia concava* Bolch., зр. 5а(2). **22**. *Marattisporites scabratus* Coup., зр. 2а(1). **23**. *Marattisporites (Punctatisporites) scabratus* Coup., зр. 3(1). **24**. *Apiculatasporites parvispinellatus* (Mal.) Sem., зр. 2а(1). **25**. *Salvinia* sp., зр. 0(1). **26**. *Clathropteris obovata* var. *magna* Tur.-Ket., 0(2). **27**. *Clathropteris obovata* var. *magna* Tur.-Ket., зр. 1а(1). **28**. *Clathropteris obovata* var. *magna* Tur.-Ket., зр. 0(1). **29**. *Leiotriletes* sp., зр. 1в(1).

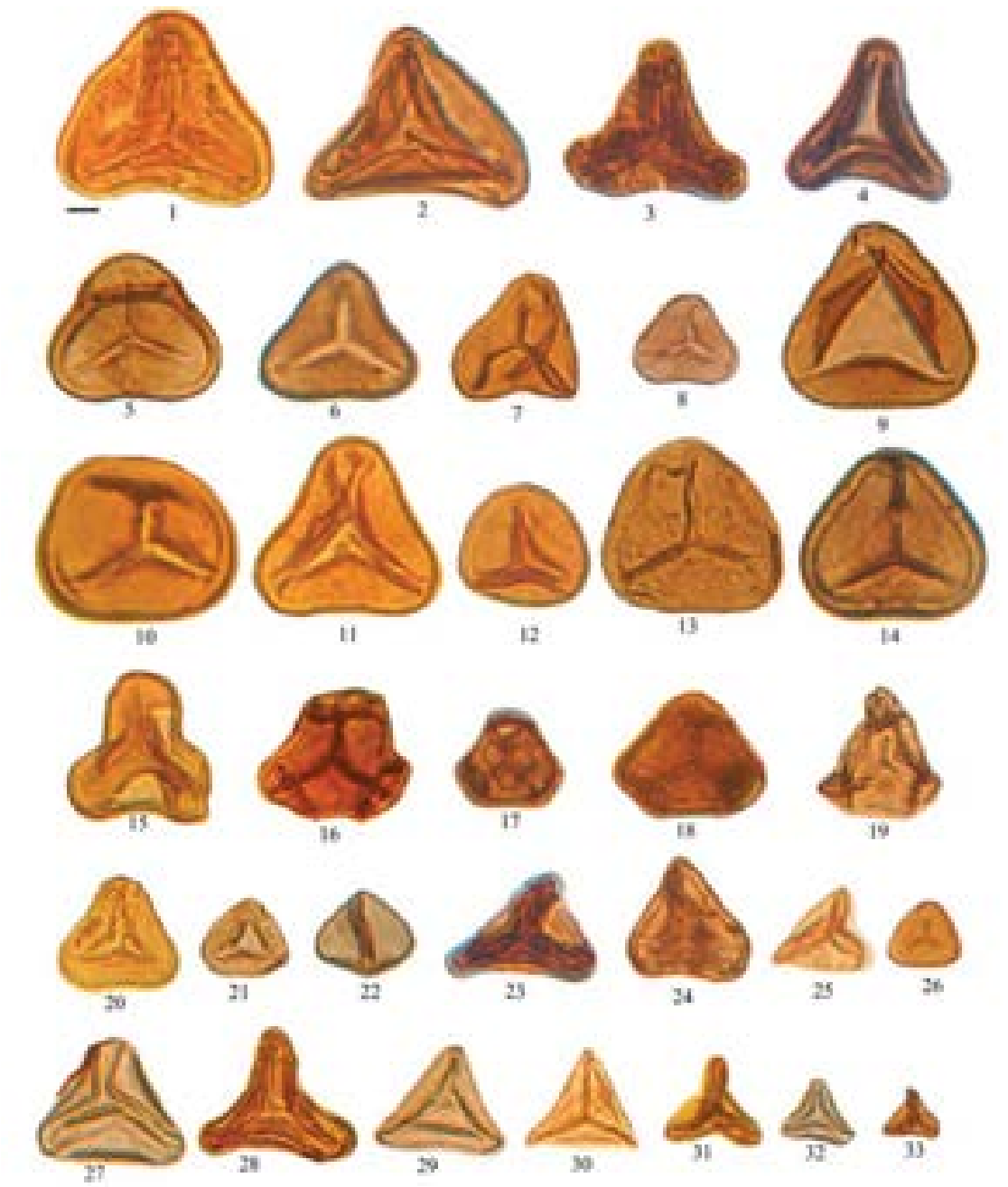


Рис. 5. Спори папоротеподібних з відкладів кам'янської світи північно-західної окраїни Донбасу. Шкала – 10 мікрон /
Fig. 5. Fern spores from the deposits of the Kamianska Formation of the northwestern outskirts of Donbas. Scale bar – 10 microns.
1. *Matoniasporites phlebopteroides* Coup., зр. 1a(1). **2**. *Matoniasporites phlebopteroides* Coup., зр. 2(1). **3**. *Phlebopteris exornatus* Bolch., зр. 5a(1). **4**. *Phlebopteris* sp., зр. 1a(1). **5**. *Cyathidites punctatus* (Del. and Sprum.) Del., Dett., Hughes, 2a(1). **6**. *Cyathidites asper* (Bolch.) Dett., зр. 2a(1). **7**. *Cyathidites subtilis* Partridge, зр. 0(1). **8**. *Cyathidites minor* Coup., зр. **9**. *Cyathidites australis* Coup., зр. 2a(1). **10**. *Concavisporites subsimplex* (Bolch.) M. Voronova, зр. 0(1). **11**. *Biretisporites* sp., зр. 5a(1). **12**. *Biretisporites spectabilis* Dett, зр. 0(1). **13**. *Biretisporites ponomarenkoae* M. Voronova, зр. 0(1). **14**. *Dictyophillidites* sp., зр. 2a(1). **15**. *Concavisporites postregularis* (Krutz.) M. Voronova, зр. 2a(2). **16**. *Concavisporites junctum* (K.-M.) Sem., зр. 3(1). **17**. *Concavisporites* sp., зр. 5a(1). **18**. *Concavisporites kainophyticus* (Krutz.) M.Voronova, зр. 0(2). **19**. *Concavisporites jurienensis* Balme, зр. 2a(1). **20**. *Coniopteris divaricata* Mal., зр. 5a(kerogen). **21**. *Coniopteris divaricata* (Mal.), зр.0(1). **22**. *Coniopteris* sp., зр. 2a(1). **23**. *Dictyophyllidites mortonii* (de Jersey) Playford and Dettmann, зр. 3(2). **24**. *Dictyophyllidites* sp., зр. 3(2). **25**. *Plicifera delicata* (Bolch.) Bolch., зр. 1a(1). **26**. *Plicifera delicata* (Bolch.) Bolch., зр. 2a(1). **27**. *Gleicheniidites angulatus* (Naum.) Bolch., зр. 2a(2). **28**. *Gleicheniidites angulatus* (Bolch.) Boch., зр. 3(1). **29**. *Gleicheniidites senonicus* Ross, зр. 2a(2). **30**. *Glecheniidites circinidites* (Cooks.) Dett., зр. 3(kerogen). **31**. *Gleicheniidites toriconcavus*? Krutzsch., зр. 5a(1). **32**. *Gleicheniidites laetus* (Bolch.) Bolch.зр. 2a(2). **33**. *Gleicheniidites laetus* (Bolch.) Bolch., зр. 2(2).



Fig. 6. Gymnosperm pollen (non-saccate) from the deposits of the Kamianska Formation of the northwestern outskirts of Donbas. Scale bar – 10 microns.

1. *Bennetites* sp., зр. 1а(1). **2.** Ginkgoales, зр. 3(1). **3.** *Cycadopites* sp., зр. 0(1). **4.** *Taxodiaceaepollenites hiatus* (Potonie) Kremp, зр. 0(1). **5.** *Equisetites variabilis* Vin., зр. 1а(1). **6.** *Exesipollenites tumulus* Balme, зр. 1а(2). **7.** *Eucomiidites troedssonii* (Erdtmann) Potonie, зр. 3(2). **8.** *Eucomiidites troedssonii* (Erdtmann) Potonie, зр. 1а(1). **9.** *Eucomiidites minor* Groot – Penny, зр. 0(1). **10.** *Chasmatosporites elegans* Nilsson, зр. 2(kerogen). **11.** *Chasmatosporites apertus* (Rogalska) Nilsson, зр. 3(1). **12.** *Classopollis classoides* (Pflug) Pocock and Jansonius, зр. 2а(2). **13.** *Classopollis* sp., зр. 2а(2). **14.** *Classopollis meyeriana* (Klaus) de Jersey, зр. 0(1). **15.** *Classopollis meyeriana* (Klaus 1960) de Jersey, зр. 2а(2). **16.** *Classopollis chateaunovi* Reyre, зр. 0(1). **17.** *Classopollis chateaunovi* Reyre, зр. 5а(2). **18.** *Classopollis simplex* (Danze-Corsin and Laveine) Reiser & Williams, зр. 1(в)1. **19.** *Callialasporites dampieri* (Balme) Dev., зр. 2а(2). **20.** *Callialasporites trilobatus* (Balme) Dev., зр. 1в(1). **21.** *Callialasporites microvelatus* Schulz, зр. 0(1). **22.** *Callialasporites segmentatus* (Balme) Srivastava, зр. 2а(1). **23.** *Cerebropollenites mesozoicus* Nilsson, зр. 1а(1). **24.** *Cerebropollenites macroverrucosus* Schulz, зр. 1а(1). **25.** *Perinopollenites elatoides* Coup., зр. 5а(1). **26.** *Araucariacites australis* Cookson, зр. 3(2).

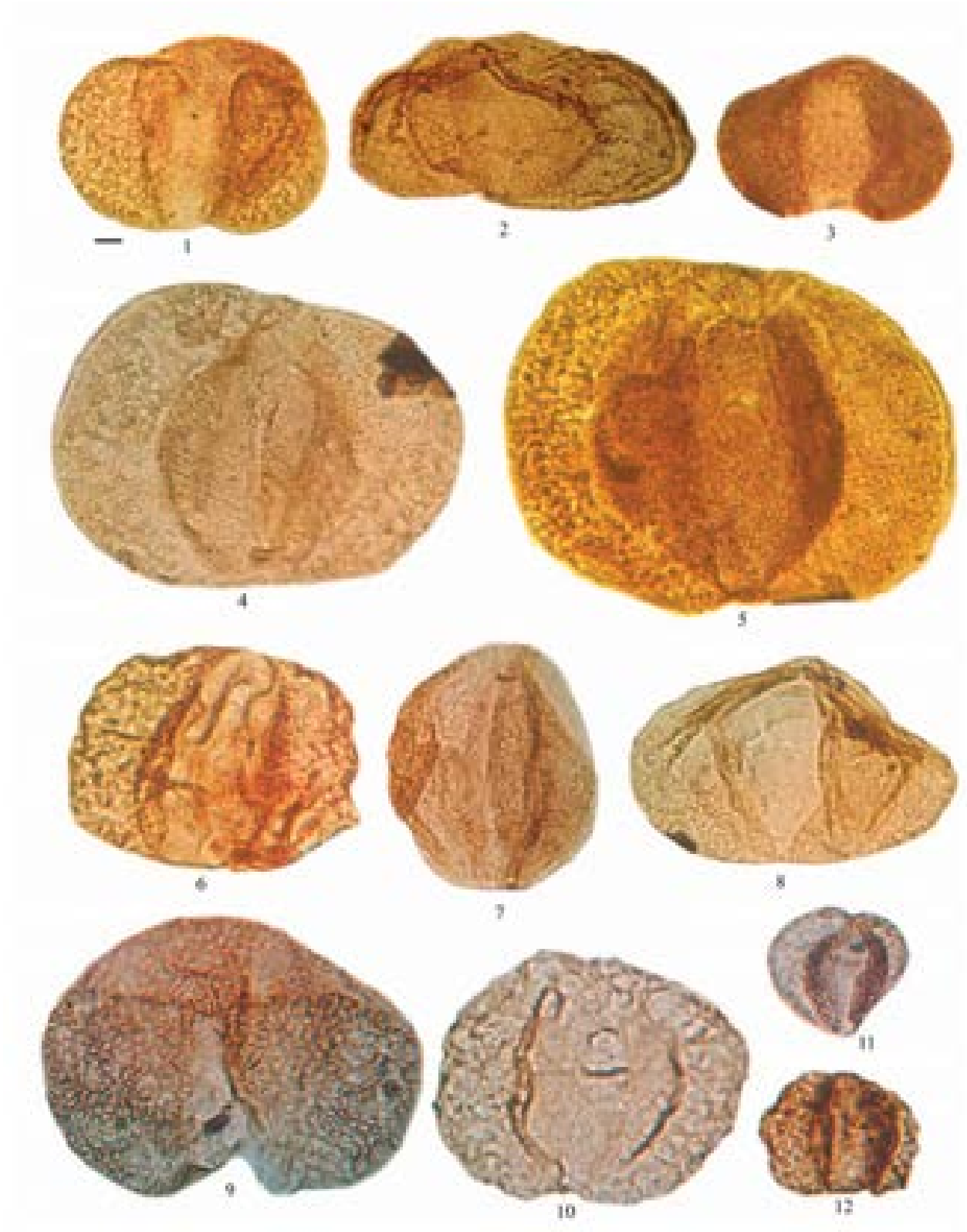


Рис. 7. Мішковий пилок голонасінних з відкладів кам'янської світи північно-західної окраїни Донбасу. Шкала – 10 мікрон /
Fig. 7. Gymnosperm pollen (saccate) from the deposits of the Kamianska Formation of the northwestern outskirts of Donbas. Scale bar – 10 microns.
1. *Pseudopiceae variabiliformis* (Mal.) Bolch., зр. 3(2). **2**. *Piceapollenites* sp., зр. 0(2). **3**. *Piceapollenites* sp., зр. 2(2). **4**. *Paleopicea* sp., рр. 1(в)1. **5**. *Pseudopiceae magnifica* Bolch., зр. 3(2). **6**. *Alisporites australis* de Jersey, зр. 3 (kerogen). **7**. *Dipterella oblatinoides* Mal., зр. 1(в)1. **8**. *Alisporites similis* (Balme) Dett., зр. 1(в)1. **9**. *Piceaepollenites exilioides* Bolch. (Petrosjanz), зр. 3 (kerogen). **10**. *Alisporites* sp., зр. 3(1). **11**. *Piceites podocarporoides* Bolch., зр. 5а(1). **12**. *Alisporites parvus* de Jersey, зр. 3(1).



Рис. 8. Мішковий пилок голонасінних з відкладів кам'янської світи північно-західної окраїни Донбасу. Шкала – 10 мікрон /
Fig. 8. Gymnosperms pollen (saccate) from the deposits of the Kamianska Formation of the northwestern outskirts of Donbas. Scale bar – 10 microns.

1. *Vitreisporites* sp., зр. 5а(1). **2**. *Vitreisporites pallidus* (Reissinger) Nilsson; Srivastava, зр. 3(1). **3**. *Pinus divulgata* Bolch., зр. 3(1). **4**. *Podocarpidites major* Coup., зр. 5а(2). **5**. *Pseudopinus* sp., зр. 5а(1). **6**. *Costatipollenites ucrainicus* Sem., зр. 3(1). **7**. *Chordasporites australiensis* de Jersey, зр. 5а(1). **8**. *Chordasporites australiensis* de Jersey, зр. 3(1). **9**. *Protopinus subluteus* Bolch., зр. 1(в)1. **10**. *Podocarpidites verrucosus* Volkheimer, зр. 1(в)1. **11**. *Podocarpidites* sp., зр. 2а(2). **12**. *Podocarpidites* sp., зр. 1(в)1. **13**. *Podocarpidites* sp., зр. 3 (kerogen). **14**. *Podocarpus proxima* Bolch., зр. 3(2). **15**. *Pinuspollenites* sp., зр. 1а(1). **16**. *Pinuspollenites* sp., зр. 3(1). **17**. *Pinuspollenites* sp., зр. 3(1). **18**. *Protopinus* sp., зр. 3(1). **19**. *Phyllocladidites* cf. *ovatus* Takahashi, зр. 5а(1). **20**. *Parvisaccites* sp., зр. 1а(1). **21**. *Quadraeculina anellaeformis* Mal. emend. Iijina., зр. 1а(1). **22**. *Quadraeculina limbata* Mal., зр. 3 (kerogen).

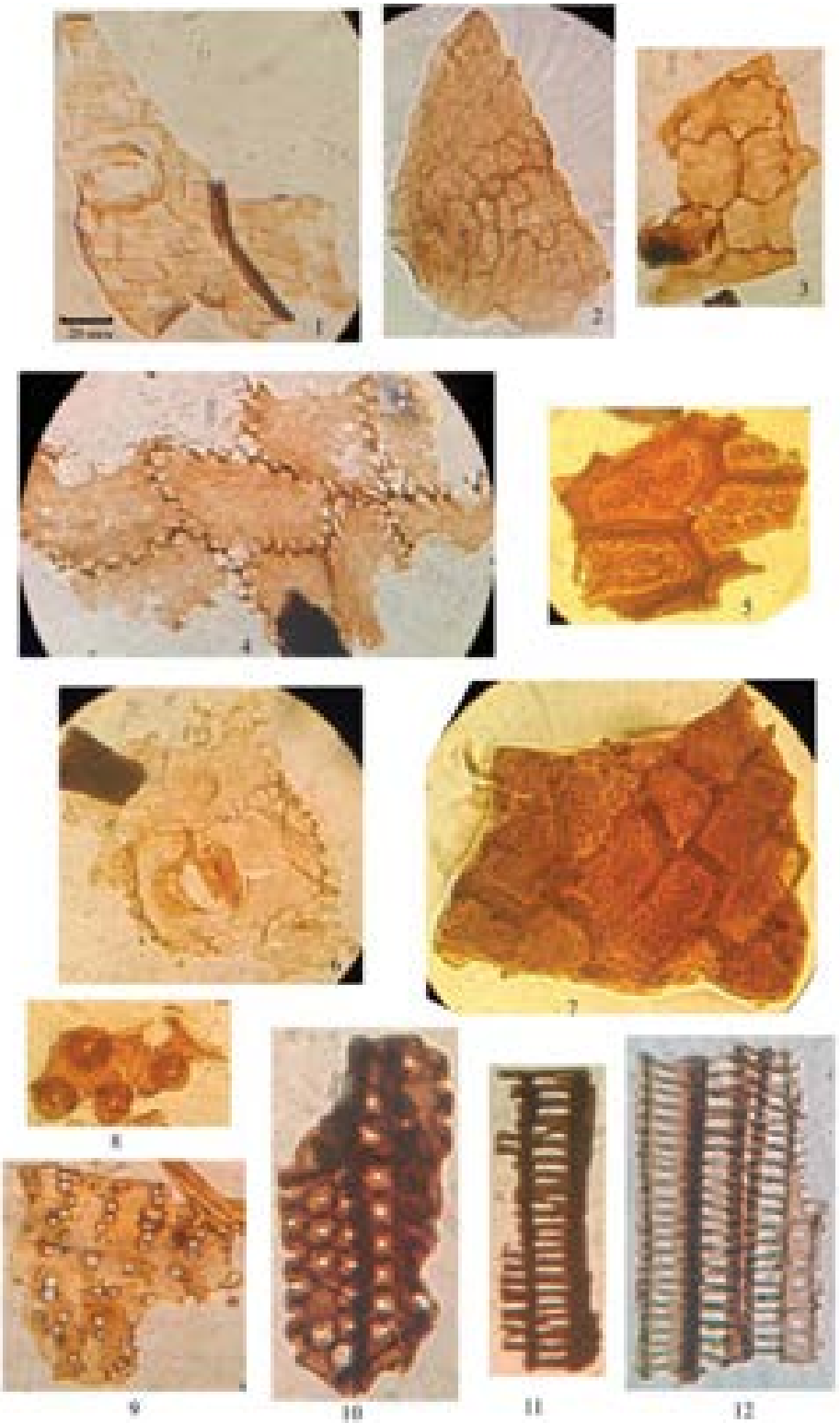


Рис. 9. Дисперсні кутикули та трахеїди з відкладів кам'янської світи північно-західної окраїни Донбасу /
Fig. 9. Dispersed cuticles and tracheids from the deposits of the Kamianska Formation of the northwestern outskirts of Donbas.
1. cf. *Solenites* cuticle, абаксіальна кутикула з одним устєм, зр.2а(1), верхній бат. **2.** *Karkenia mongolica* Krassil., абаксіальна кутикула. зр.2а(1), верхній бат. **3.** cf. *Marskea jurassica* (Florin) - conifer cuticle, адаксіальна кутикула, зр.1b(1), верхній бат. **4.** Bennettitalean кутикула з підкріпленими антиклінальними клітинними стінками (cuticle with buttressed anticlinal cell walls), зр.1а(1), верхній бат. **5.** Conifer cuticle (similar to *Brachyphyllum* and *Pagiophyllum* spp.), адаксіальна кутикула, зр. 3(1) середній бат. **6.** Bennettitalean cuticle with paracytic stomate, абаксіальна кутикула, що містить устєвий апарат, зр.1а(1), верхній бат. **7.** Адаксіальна кутикула хвойних (conifer cuticle, similar to *Pagiophyllum* spp.), зр.1а(2), верхній бат. **8.** Неприлягаючі облямовані ямки на фрагменті трахеїди (non-abutting bordered pits on a tracheid fragment), зр. 1в(1), верхній бат. **9.** Фрагменти трахеїд з простим круговим перехресним ямуванням (tracheid fragments with simple circular cross-field pitting), зр. 2(1), середній бат. **10.** Multiseriate contiguous bordered pits on tracheid fragments (multiseriate contiguous bordered pits on tracheid fragments), зр. 2(2), середній бат. **11.** Вузька скаляріформна ямка на можливій трахеїді папороті або плауна (narrow scalariform pitting on possible fern or lycopsid tracheid), зр. 0(1), середній бат. **12.** Широкі скаляріподібні та прилеглі односерійні облямовані ямки на можливих трахеїдах первинної ксилеми голонасінних (broad scalariform and adjacent uniseriate bordered pitting on possible gymnosperm primary xylem tracheids), зр. 0(1), середній бат./

Середня швидкість осадконакопичення протягом пізнього бату досить висока та складає до 12 см/тис. років, що відповідає швидкості накопичення сучасних алювіальних відкладів.

Висновки

Вік кам'янської світи – середній-пізній бат, обґрунтований та підтверджений макрофлорами та даними палінолоічного аналізу, також стратиграфічним положенням у розрізі.

У макрофлористичному та мезофлоральному (кутикула) комплексах кам'янської світи переважають папороті але також містить набір сфенопсидів (*Neocalamites*), беннетитових (*Ptilophyllum*), гінкгових (*Ginkgodium*), хвойних рослин (*Pagiophyllum*) та деякі рештки голонасінних рослин невизначеної спорідненості (наприклад, *Taeniopteris* та коріння). Склад флори відповідає типовому європейському флористичному комплексу середньої юри та вказує на розвиток вологої низинної рослинності, пов'язаної з дельтовими та алювіальними середовищами. Водночас, зростання кількості хвойних залишків у верхній частині формації свідчить про поступові зміни навколишнього середовища та клімату в бік більш посушливих умов.

У складі спорового комплексу кам'янської світи домінують трилетні спори, представлені формами, близькими до родів *Cyathidites, Osmundacidites* та *Gleicheniidites*. Їх значна частка свідчить про широке поширення вологолюбної папоротевої рослинності в умовах осадконакопичення. Пилковий комплекс представлений переважно голонасінними, зокрема таксонами, пов'язаними з родинами Cupressaceae, Cheirolepidiaceae та Araucariaceae. Наявність пилку типу *Classopollis, Perinopollenites* та *Araucariacites* вказує на розвиток хвойних угруповань, також адаптованих до відносно більш сухих умов.

Важливою особливістю є зміна співвідношення спор і пилку по розрізу: у нижній частині переважають спори, тоді як у верхній частині відзначається збільшення частки пилку голонасінних. Така тенденція може відображати поступову зміну палеоекологічних умов – від більш вологих до відносно посушливих.

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Внесок авторів: всі автори зробили рівний внесок у цю роботу.
Конфлікт інтересів: автори повідомляють про відсутність конфлікту інтересів.
Декларація про використання генеративного штучного інтелекту: автори підтверджують, що під час підготовки рукопису не використовувалися інструменти штучного інтелекту.

Authors Contribution: All authors have contributed equally to this work
Conflict of Interest: The authors declare no conflict of interest

Declaration of use of generative artificial intelligence: The authors confirm that no AI tools were used during the preparation of the manuscript.

Jurassic system stratigraphy at the Kamianka village. Part 4. The Kamianska formation

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ABSTRACT

Introduction. This study focuses on the Jurassic Kamianska Formation of northwestern Donbas, eastern Ukraine and is part of a series of publications concerning Jurassic stratigraphy in the vicinity of the village of Kamianka. The study is especially important because as we here document several classical outcrops containing rich macrofloral assemblages, localities that are in the risk of being damaged, inaccessible, or permanently destroyed due to ongoing military activities in the region.
Material and methods. The study is based on lithological observations and fossils collected from Middle Jurassic deposits of the northwestern Donbas. The focus of the study are the palynological asseblages including the palynoflora and the macroflora, combined with sedimentological data from outcrops. Palynological samples were processed using standard laboratory techniques, including acid maceration, sieving, and microscopic analysis.
Results and discussion. The investigated Bathonian deposits yield diverse palynological assemblages dominated by fern spores and gymnosperm pollen. The most common spores belong to the fern families Gleicheniaceae, Osmundaceae, and Cyatheaceae, whereas gymnosperm pollen is represented mainly by *Classopollis, Callialasporites, Perinopollenites,* and *Araucariacites*. The composition of the assemblages indicates that the plants producing these pollen and spores grew in a humid warm-temperate environment. Increased abundance in the upper part of the section of *Classopollis*, produced by the drought-adapted Cheirolepids, suggests gradual climatic drying during the late Bathonian.
Lithology. The Bathonian deposits are composed predominantly of alternating sandstones, siltstones, carbonaceous claystones . The lower part is sandy, whereas the upper part is mainly clayey with coal lenses, fossil wood, and volcanogenic material. Sedimentary structures indicate deposition within fluvial, deltaic, lagoonal, and marginal-marine environments.
Stratigraphy. Integrated paleobotanical and palynological data confirm the Bathonian age of the Kamianska Formation. The investigated palynological assemblages correlate well with coeval assemblages from Scandinavia and other European regions, particularly with the Callialasporites–Perinopollenites palynozone.
Conclusion. The Kamianska Formation represents an important middle–upper Bathonian unit, located in the northwestern Donbas, Ukraina. The dating of the succession is based on integrated lithological, macrofloral, and palynological analyses documenting a gradual paleoenvironmental changes from humid to relatively drier conditions during time of the sediment accumulation. The late Bathonian macroflora is dominated by ferns and Bennettites accompanied by horsetails, ginkgophytes, and conifers, reflecting vegetation typical of the Middle Jurassic European floral province. The palynological assemblages demonstrate strong similarities with coeval European floras and provide an important basis for regional Jurassic stratigraphic correlations and paleoenvironmental reconstructions.

ARTICLE INFO

Manuscript received
3 April 2026

Revised manuscript received
20 May 2026

Manuscript accepted
25 May 2026

Available online
30 May 2026

Keywords:

fossils, palynological data, macroflora, stratigraphy, Jurassic, Bathonian, Kamianska Formation, lithology, North-Western Donbas, Ukraine.

In cites: Matveev Andriy, Shevchuk Olena, Vajda Vivi, McLoughlin Stephen (2026). Jurassic system stratigraphy at the Kamianka village. Part 4. The Kamianska formation. *Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology*, (64), 78–94. https://doi.org/10.26565/2410-7360-2026-64-06 [In Ukrainian]

https://doi.org/10.26565/2410-7360-2026-64-07

UDC 553.98:552.578.2:550.822

Statistical and 3D Petrophysical Analysis of Reservoir Formations and Net Pay Thickness of the Mamuniyat Formation, Sharara B-Oil Field, Murzuq Basin, Libya

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ABSTRACT

Problem Statement and Purpose. This study presents a comprehensive statistical analysis and three-dimensional (3D) petrophysical modeling of the Mamuniyat Formation in the Sharara B-Oil Field, Murzuq Basin, Libya. The primary objective is to evaluate reservoir quality and spatial heterogeneity by integrating well-log data with geostatistical simulations using industry-standard petrophysical methods. Through rigorous characterization of effective porosity and fluid saturation distributions, combined with strict net pay cutoff enforcement (Φe ≥ 10%, Vsh ≤ 30%, Sw ≤ 60%), the research identifies the most promising hydrocarbon-bearing zones and establishes a reproducible framework for reservoir evaluation in data-limited settings.
Data and Methods. An integrated statistical and 3D petrophysical characterization was performed based on quantitative analysis of wireline log data from nine wells (B01, B03, B05, B10, B12, B13, B15, B19, B29). Key methodological improvements include effective porosity derived from density logs with shale correction (Φe = Φt × [1−Vsh]) and water saturation calculated using Murzuq Basin-calibrated Archie parameters (Rw = 0.08 Ω·m at 70°C). For wells lacking legacy saturation curves, values were deterministically reconstructed to ensure dataset completeness. Petrophysical properties were spatially distributed using Sequential Gaussian Simulation within a structurally constrained 3D framework, with model accuracy confirmed by blind-well validation.
Hydrocarbon Potential Score (HPS). The HPS is a composite multi-criteria index on a 0 to 1 scale, designed for objective reservoir ranking by integrating normalized petrophysical parameters weighted as follows: effective porosity (40%), water saturation (25%), shale volume (15%), total porosity (15%), and net pay thickness (5%). Unfavorable parameters were inverted during normalization to ensure higher scores consistently reflect superior reservoir quality. The HPS was calibrated against volumetric hydrocarbon indicators (net pay thickness × oil saturation) to align quality assessments with actual hydrocarbon column heights.
Results and Discussion. Results reveal pronounced vertical compartmentalization within the Mamuniyat Formation. The Upper Mamuniyat is identified as the primary reservoir target, exhibiting superior fluid properties (average Sw = 31.0%, So = 69.0%), consistent net pay distribution across the field (average thickness 7.1 meters), and the highest HPS score (0.81). The Lower Mamuniyat serves as a secondary target with highly localized commercial potential; its field-wide average net pay thickness is limited to 2.1 meters and confined to structurally elevated zones in the B15 and B29 blocks where hydrocarbon column preservation occurs. Seven wells display minimal Lower Mamuniyat net pay due to proximity to the regional oil-water contact (Sw = 64–75%). The Middle Mamuniyat is consistently non-commercial (average Sw = 82.0%, Φe = 9.2%) and functions as a vertical flow barrier. Corrected volumetric analysis confirms that the Upper Mamuniyat contributes approximately 6.9 times more hydrocarbon volume per well than the Lower Mamuniyat (hydrocarbon column: 4.90 meters versus 0.71 meters), establishing it as the optimal development target.

ARTICLE INFO

Manuscript received
9 January 2026

Revised manuscript received
23 March 2026

Manuscript accepted
25 May 2026

Available online
30 May 2026

Keywords:

Mamuniyat Formation, reservoir characterization, net pay, oil saturation, 3D geostatistical modeling, Murzuq Basin, Libya.

In cites: Saadi Nureddin, Amish Ibrahim, Alzorqani Ahmed (2026). Statistical and 3D Petrophysical Analysis of Reservoir Formations and Net Pay Thickness of the Mamuniyat Formation, Sharara B-Oil Field, Murzuq Basin, Libya. *Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology*, (64), 95–108. https://doi.org/10.26565/2410-7360-2026-64-07

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Introduction

Porosity and water saturation are fundamental petrophysical properties essential for evaluating and characterizing hydrocarbon reservoirs [1]. Accurate petrophysical assessment is critical for effective reservoir estimation and modeling, which supports optimized production and development strategies [2]. The Sharara Oil Field, discovered in 1995 by the Libyan National Oil Corporation (NOC), is located in southwest Libya within the southern part of concession NC 115 in the Murzuq Basin, approximately 1000 kilometers south of Tripoli. It ranks among Libya's largest oil fields, with estimated reserves exceeding 11 billion barrels of crude oil and a production capacity of up to 350,000 barrels per day. Historically operated by international companies such as Repsol, Total, and Eni, the field is currently managed by Akakus Oil Operations [3, 4].

The Murzuq Basin hosts extensive Paleozoic clastic reservoirs, with the Ordovician-Silurian Mamuniyat Formation representing a major hydrocarbon-bearing unit across the basin. Within the Sharara field complex, the Mamuniyat Formation is subdivided into three distinct stratigraphic members: Upper, Middle, and Lower [5]. This study demonstrates that these members exhibit unique petrophysical signatures and pressure-barrier characteristics that dictate the field's overall plumbing system. Although previous studies have established the regional depositional framework and broad reservoir properties of the Mamuniyat Formation, significant challenges remain in translating statistical petrophysical averages into reliable assessments of commercial hydrocarbon potential, especially when critical saturation data are missing from legacy logging suites.

A persistent limitation in characterizing Paleozoic clastic reservoirs is the reliance on porosity based statistics without explicitly determining net hydrocarbon bearing thickness and oil saturation. Statistical averages of effective porosity or shale volume can be misleading in heterogeneous reservoirs, as they do not distinguish between high quality rock intervals that are water wet and those containing producible hydrocarbons. This distinction is particularly important in structurally complex intracratonic basins, where proximity to the oil water contact strongly influences fluid distribution [6].

This study addresses this gap through integrated petrophysical analysis and three dimensional modeling of the Mamuniyat Formation in the Sharara B Oil Field. Well log data from nine wells including gamma ray, bulk density, and deep resistivity measurements are used to calculate key reservoir parameters following industry standard methodologies. For wells B03, B05, and B12, where water saturation curves were unavailable, values were deterministically reconstructed using raw resistivity and density derived porosity to ensure a complete field wide evaluation. These well data are integrated into a field-scale structural framework derived from well-top correlations, allowing for the spatial mapping of reservoir properties relative to the field's structural relief and fluid contacts. Central to this workflow is the explicit determination of net pay thickness through rigorous simultaneous application of cutoff criteria for effective porosity, shale volume, and water saturation [7, 8].

To enable objective reservoir quality ranking, a Hydrocarbon Potential Score (HPS) is utilized as a normalized multi parameter index integrating effective porosity with 40 %t weight, water saturation 25 %, shale volume 15 %, total porosity 15 %, and net pay thickness 5 %. Parameters are normalized on a zero to one scale with unfavorable variables inverted to ensure higher scores consistently reflect better reservoir quality [9]. The score is calibrated using volumetric hydrocarbon indicators—specifically the hydrocarbon column height (H × So)—to ensure that reservoir quality rankings accurately reflect movable oil volumes and commercial potential.

In the absence of seismic data, a three-dimensional reservoir model is constructed using Sequential Gaussian Simulation (SGS) within Petrel software. This model incorporates well tops and upscaled petrophysical properties to generate continuous distributions of effective porosity and oil saturation across the field [10]. The geostatistical approach honors well data while capturing lateral and vertical heterogeneity typical of glacial-related reservoir systems. The model's predictive accuracy is confirmed through blind-well validation, ensuring spatial distributions are geologically representative. While the resulting distributions are log-derived estimates in the absence of core calibration, the integration of multiple petrophysical parameters and blind-well validation ensures a high degree of reliability for the model's spatial predictions.

This study establishes a reproducible workflow for reservoir characterization in data limited settings by integrating rigorous petrophysical calculations with volumetric parameter determination and spatial modeling. The methodology provides a robust framework to distinguish productive hydrocarbon intervals from water bearing zones in Paleozoic clastic reservoirs, with direct applications for optimizing well placement and completion strategies in the Murzuq Basin and similar intracratonic environments.

Geological Setting of Murzuq Basin

The Murzuq Basin, a vast intracratonic basin in the North African platform, covers over 350,000 km² [11, 12]. Its current geological boundaries, shaped by multi-phase tectonic uplifts, differ significantly from the broader early Paleozoic North African sedimentary basin [12, 13]. Although multiple fault generations are recognized, the resulting deformation is relatively minor [12] (Fig. 1).

The basin contains up to 4000 m of sedimentary fill, mainly marine Paleozoic and continental sequences [12, 14]. The primary hydrocarbon play is an Ordovician periglacial sandstone reservoir [11, 15], sealed and sourced by overlying Silurian shale [15], yielding about 1500 million barrels of recoverable oil to date [11]. Oil generation likely occurred during the Cretaceous [11], though further study is needed to clarify timing. Subsequent regional uplift and erosion cooled source rocks, halting further oil generation over much of the basin [11]. The Silurian source rock remains within the oil generation window only in a limited central area [11] (Fig. 2).

Petroleum system effectiveness and the oil column thickness in the Sharara field depend directly on the reservoir's structural elevation relative to the regional oil-water contact. Thus, quantifying net pay thickness (H) is critical, as structural position determines whether high-quality sandstone is oil-bearing or water-saturated.

The modern Murzuq Basin formed during the Mesozoic; before that, the Paleozoic basin featured NW-SE trending highs and lows [3, 16]. Fault density and structural complexity increase from the stable south toward the more faulted northeast and northwest, with the Tiririne and Traghan highs showing the most intense faulting [3].

The Mamuniyat Formation (Late Ordovician) is a key oil reservoir, consisting mainly of interbedded sandstones, shales, and siltstones [15]. It is subdivided into Lower (LM), Middle (MM), and Upper (UM) units, identifiable in outcrops and subsurface [15]. This study evaluates the oil saturation (So) across these units to differentiate productive hydrocarbon zones from intervals influenced by formation water. While the Upper Mamuniyat is the main target, the Middle and Lower units show significant petrophysical heterogeneity that requires volumetric analysis to assess their reservoir potential.

Petroleum System of Murzuq Basin

The Murzuq Basin, situated in southwestern Libya, is a prolific intracratonic sag basin characterized by a petroleum system dominated by Paleozoic strata, primarily defined through the Tanezzuft Mamuniyat/Hawaz play. Central to this system is the Lower Silurian Tanezzuft Formation, notably its basal "Hot Shale" member, which constitutes the principal hydrocarbon source rock. Geochemical investigations have demonstrated exceptionally high organic richness within this interval, with Total Organic Carbon (TOC) values reaching up to 17% in localized depocenters where anoxic depositional conditions enabled excellent preservation of organic matter [20]. Across multiple wells in License NC-115, average TOC values range from 4.5% to over 10%, establishing the Hot Shale as an excellent oil- and gas-prone source rock dominated by kerogen types II and III [21]. Complementary Rock-Eval pyrolysis and biomarker analyses indicate that this unit presently resides within the early oil maturity window in most areas, although regional variations reflect differing burial depths and thermal histories [22].

Hydrocarbon generation in the basin has been strongly influenced by its complex tectonostratigraphic evolution, including reactivation phases linked to the Caledonian, Hercynian, and Alpine orogenic events. These tectonic episodes produced variable subsidence, uplift, and heat flow regimes across the basin. Thermal modeling suggests that initial maturation commenced during the Late Paleozoic, while the principal phase of oil generation and expulsion occurred in the Mesozoic, particularly throughout the Cretaceous period. This timing corresponds with increased burial depths and elevated geothermal gradients, which drove the Hot Shale into peak oil generation [23, 24].

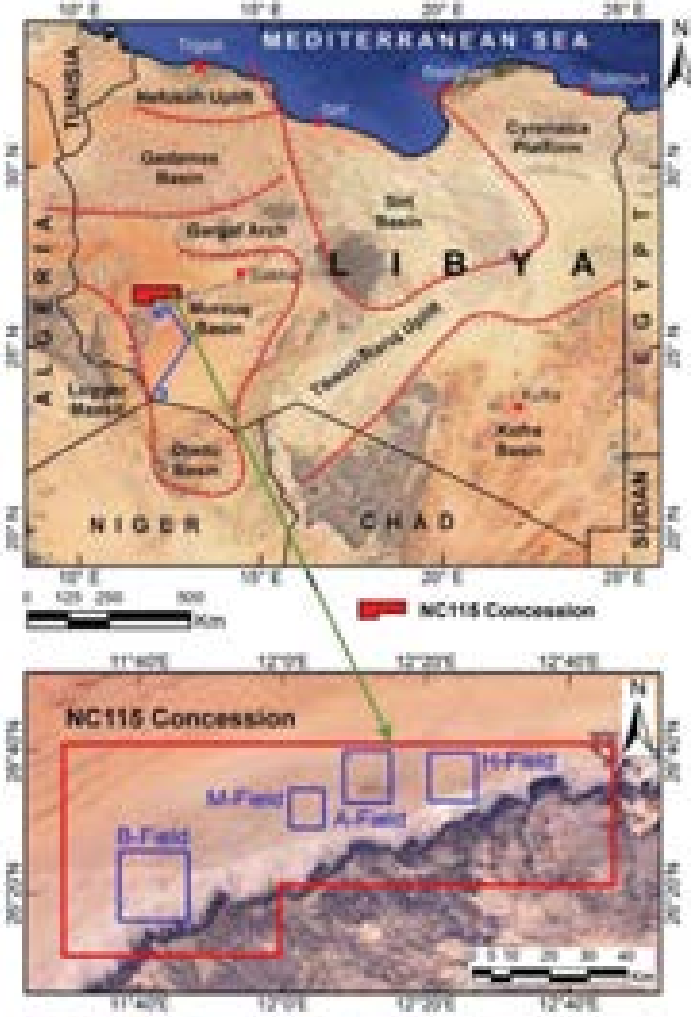


Fig. 1. Map of Libya showing major sedimentary basins, the NC115 Concession, and its oilfields. Basin boundaries adapted from [17] as cited in [18].

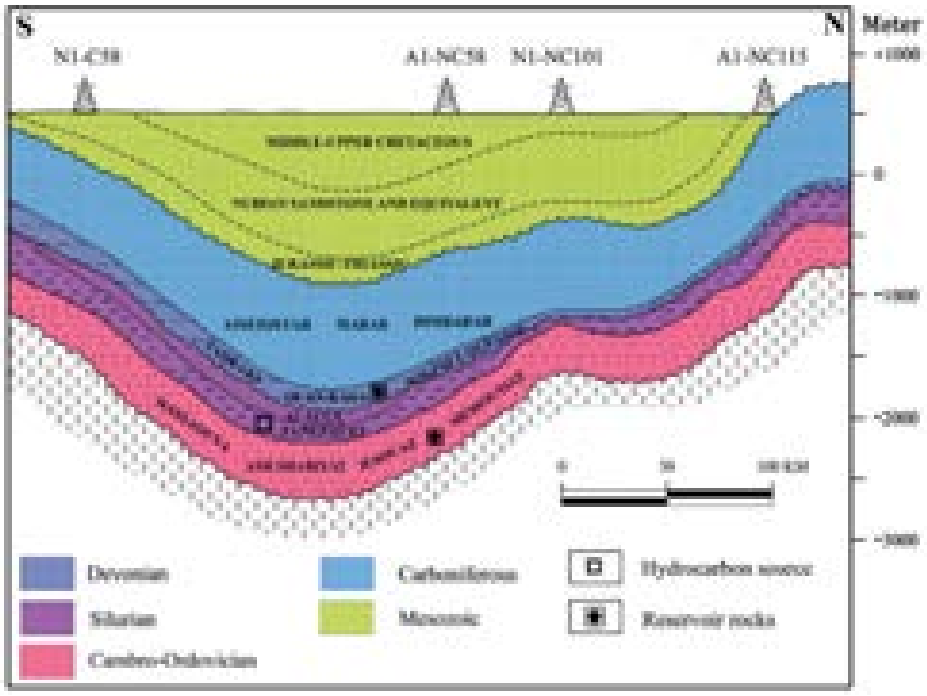


Fig. 2. North–south cross-section of the Murzuq Basin (after [19] as cited in [18]). The cross-section location is shown in Fig. 1.

The synchronization of hydrocarbon generation with structural trap formation facilitated effective migration and entrapment into underlying reservoir units. In the Sharara B Oil Field, the effectiveness of this entrapment and the resulting oil saturation (So) are highly dependent on the vertical proximity to the Tanezzuft source and the structural seal integrity, which ultimately determines the net pay thickness (H).

The primary reservoirs are the Upper Ordovician Mamuniyat Formation and the Middle Ordovician Hawaz Formation, both comprised of siliciclastic sediments deposited under distinct paleoenvironmental conditions. The Mamuniyat Formation features fluvial to shallow marine sandstones, frequently filling incised valleys formed during the Hirnantian glaciation, and exhibits favorable petrophysical characteristics with porosities exceeding 20% and permeabilities above 100 millidarcies in key fields [25, 26]. Similarly, the Hawaz Formation consists of tidally influenced, fine-grained quartzarenites with good reservoir quality, notably on structural highs where diagenetic alteration was minimal [27, 28]. Seismic data reveal well-developed channel systems and onlap and truncation geometries consistent with valley-fill depositional settings, underscoring their role as major hydrocarbon-bearing intervals [25, 29]. While these units have significant gross thickness, the actual net pay (H) is often vertically restricted. In this study, the volumetric evaluation confirms that productive oil saturation (So) is concentrated in the Upper Mamuniyat, whereas the deeper intervals often transition into formation water-bearing zones.

Seal integrity for these reservoirs is provided by the overlying Tanezzuft shales, which function as both top and lateral seals due to their extensive regional distribution, ductile nature, and extremely low permeability. Their thickness and lateral continuity ensure effective stratigraphic containment, especially when combined with structural features such as faulted anticlines and paleo-highs linked to basement-involved tectonics [23, 30]. Integrated seismic and well-log analyses confirm strong source reservoir seal configurations throughout the basin, solidifying its position as one of the most significant hydrocarbon provinces in North Africa [25, 31]. The interplay of high-quality source rocks and effective seals defines the hydrocarbon column, where the oil saturation (So) remains highest in structurally elevated zones and diminishes toward the regional oil-water contact, where formation water becomes dominant.

Methodology

Nine wells (B01, B03, B05, B10, B12, B13, B15, B19, and B29) were analyzed using Gamma Ray (GR), Bulk Density (RHOB), and Deep Resistivity (LLD/LLS) logs, sampled at 0.5-foot intervals (Fig. 3). The Mamuniyat Formation was subdivided into Upper, Middle, and Lower members using formation tops validated through GR and sonic log correlation. To ensure a consistent spatial framework, these vertical subdivisions were integrated into a 3D stratigraphic reconstruction (Fig. 4). This step was essential to verify the lateral correlation and stacking patterns of the members across the study area prior to the calculation of petrophysical averages. Lithology was further confirmed via density-neutron crossplots to ensure sandstone identification and eliminate gas-crossover effects (Fig. 5).

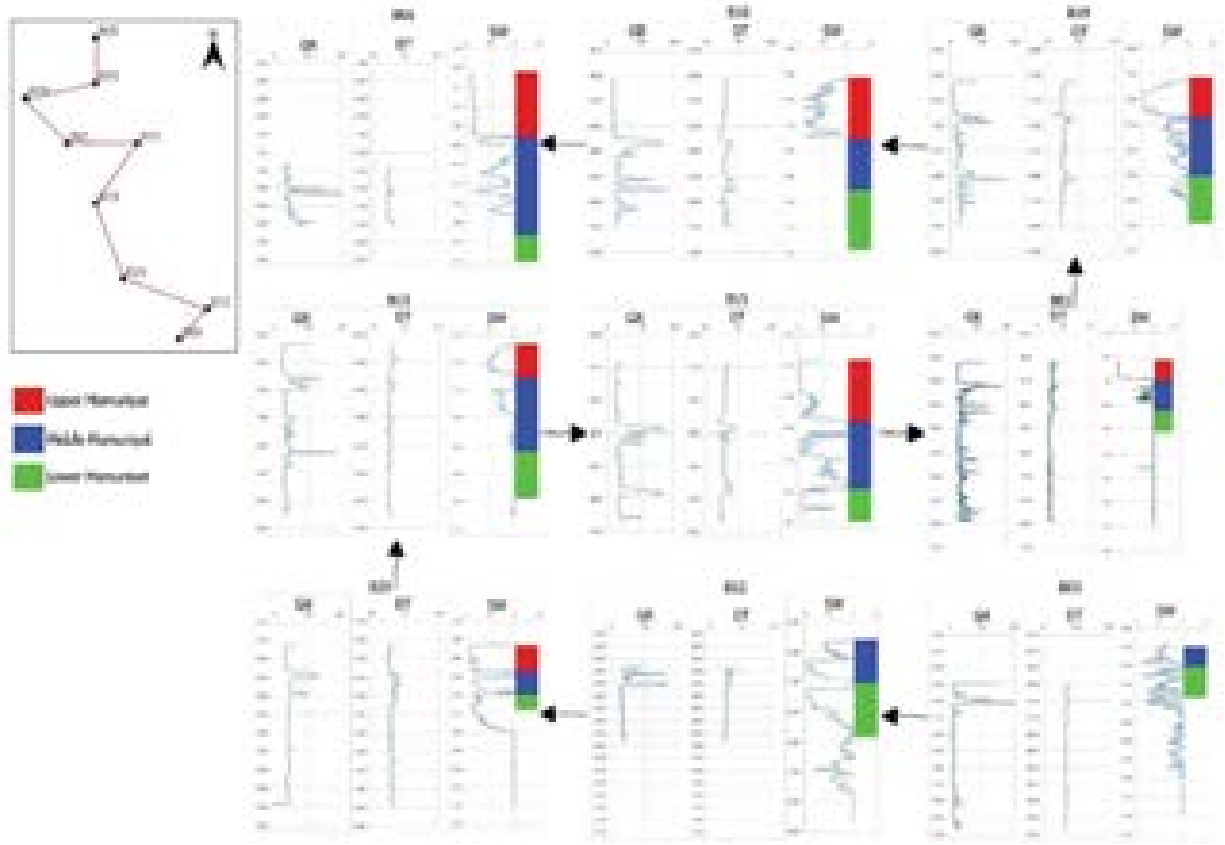


Fig. 3. Structural petrophysical correlation across the study area (S-N transect). The section illustrates the stratigraphic continuity of the Upper, Middle, and Lower Mamuniyat members. Note the Middle Member acting as a field-wide shale-rich vertical flow barrier, effectively isolating the primary Upper reservoir from the Lower reservoir units.

Volume of Shale (Vsh) Determination

Shale volume was calculated using the linear gamma ray method with basin-calibrated baselines [1]:

$Vsh = (GR_{log} – GR_{min}) / (GR_{max} – GR_{min})$ where GR_{min} = 20 API (clean sand baseline) and GR_{max} = 100 API (shale baseline), verified across all wells. Vsh values were constrained to the 0.0–1.0 range to ensure physical validity.

Total and Effective Porosity Determination

Total porosity (Φt) was derived exclusively from bulk density logs using the standard sandstone matrix density [1]:

Φt = (2.65 - RHOB) / 1.65 where RHOB is bulk density in g/cc and 2.65 g/cc represents quartz matrix density. Effective porosity (Φe) was calculated using shale-corrected density porosity as required by industry standards: Φe = Φt × (1 − Vsh) This approach eliminates the significant porosity underestimation inherent in non-standard methods. Secondary porosity calculations were excluded

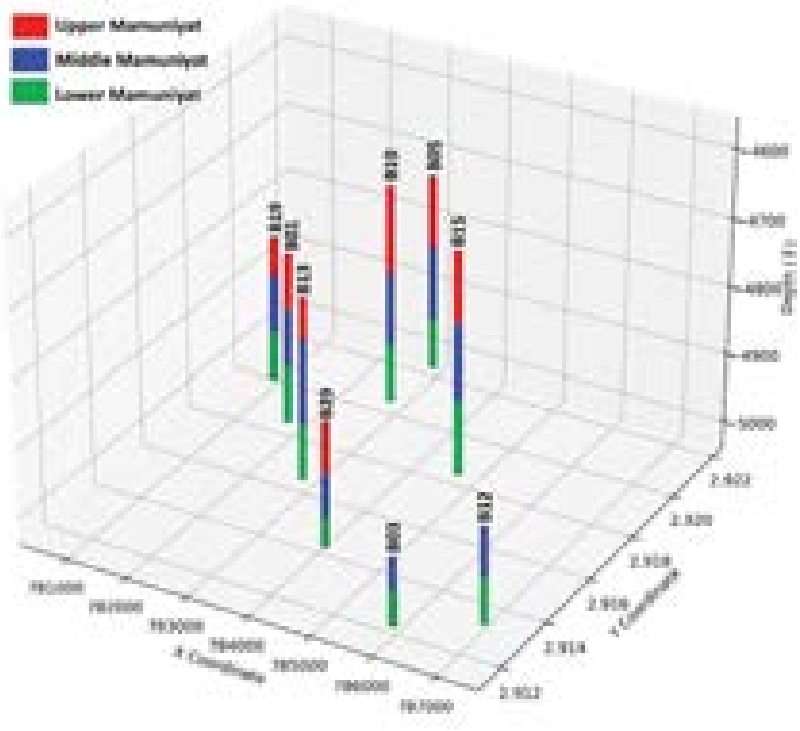


Fig. 4. 3D subsurface model illustrating well trajectories and lithological intervals. The visualization highlights the clear three-member subdivision of the Mamuniyat Formation throughout the study area. Colors indicate the Upper Member (red), Middle Member (blue), and Lower Member (green).

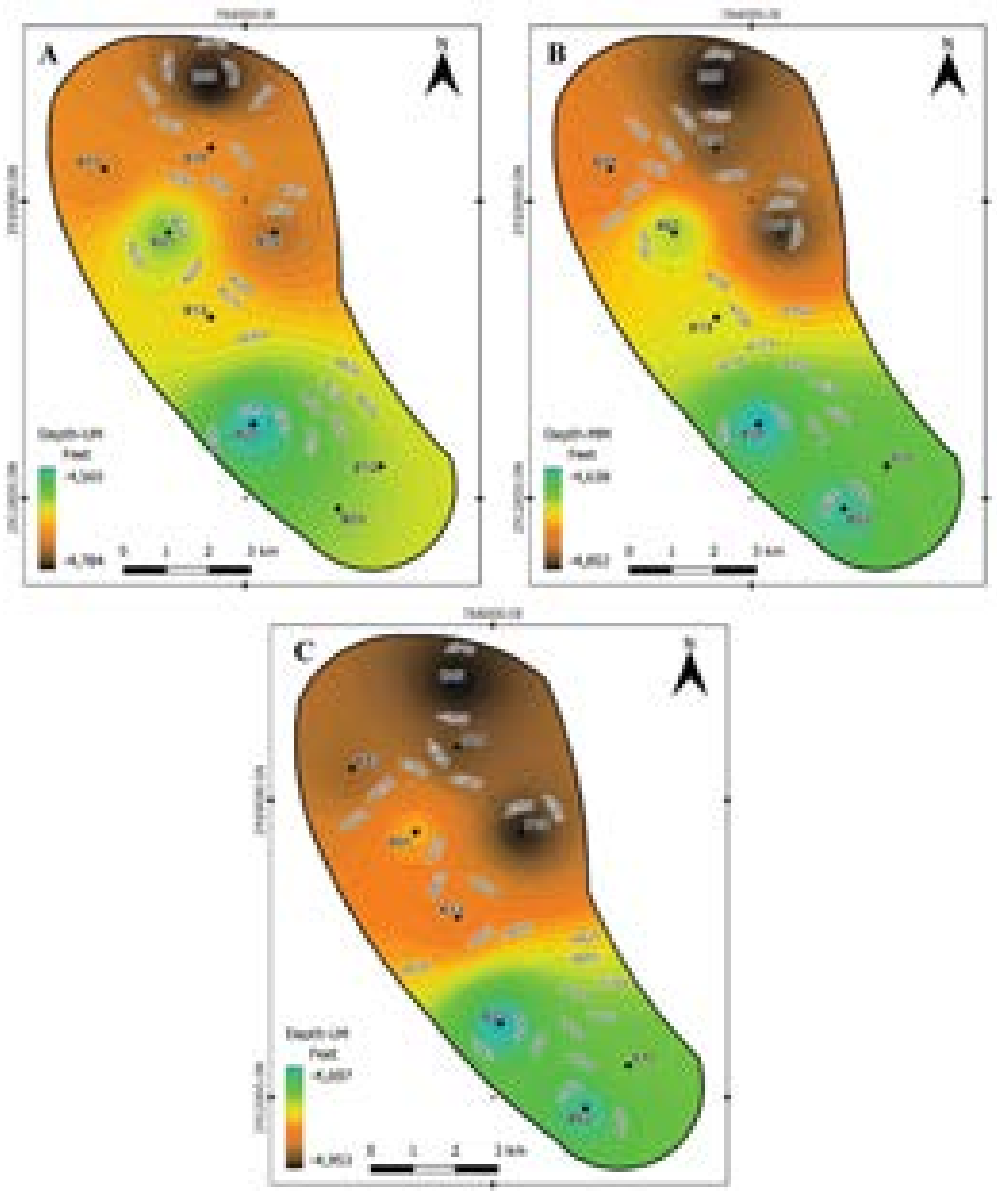


Fig. 5. Structural contour maps of the Mamuniyat Formation in the study area. (A) Top Upper Mamuniyat member, showing the localized distribution and pinch-out towards the Southwest; (B) Top Middle Mamuniyat member, representing the continuous field-wide structural framework; (C) Top Lower Mamuniyat member. Contours are in feet below sea level (TVDSS), highlighting the structural high in the Northeastern sector.

as they do not correlate with permeability in these tight sandstones.

Water and Oil Saturation Determination

Water saturation (Sw) was computed using Archie's equation with Murzuq Basin standard parameters [32]:

with a = 1.0, m = 2.0, n = 2.0, and Rw = 0.08 Ω·m @ 70°C. For wells B03, B12 (Upper Mamuniyat), and B05 (Lower Mamuniyat) where Sw curves were unavailable, values were deterministically reconstructed from raw Rt and density logs to ensure field-wide dataset integrity. All saturation values were calculated as fractions for mathematical operations and subsequently converted to percentages for reporting and visualization. Oil saturation was calculated as So = 1 – Sw.

Net Pay Definition and Thickness Calculation

Net pay intervals required strict simultaneous satisfaction of all three industry-standard cutoffs: Φe ≥ 10%, Vsh ≤ 30%, and Sw ≤ 60% (So ≥ 40%). Intervals failing any single criterion were excluded regardless of gross thickness [8]. Total net pay thickness (H) was calculated by summing 0.5-ft depth increments meeting all three criteria.

Quality Control Protocol

All calculations underwent mandatory three-tiered validation: depth consistency (0.5-ft sampling), parameter range verification (RHOB: 2.0–2.8 g/cc; GR: 15–150 API), and physical consistency checks (Φe ≤ Φt and Sw ≥ So) [33].

Hydrocarbon Potential Score (HPS) Formulation

The HPS was created as a composite multi-criteria index to objectively rank reservoir quality. Parameters were normalized to a 0–1 scale,

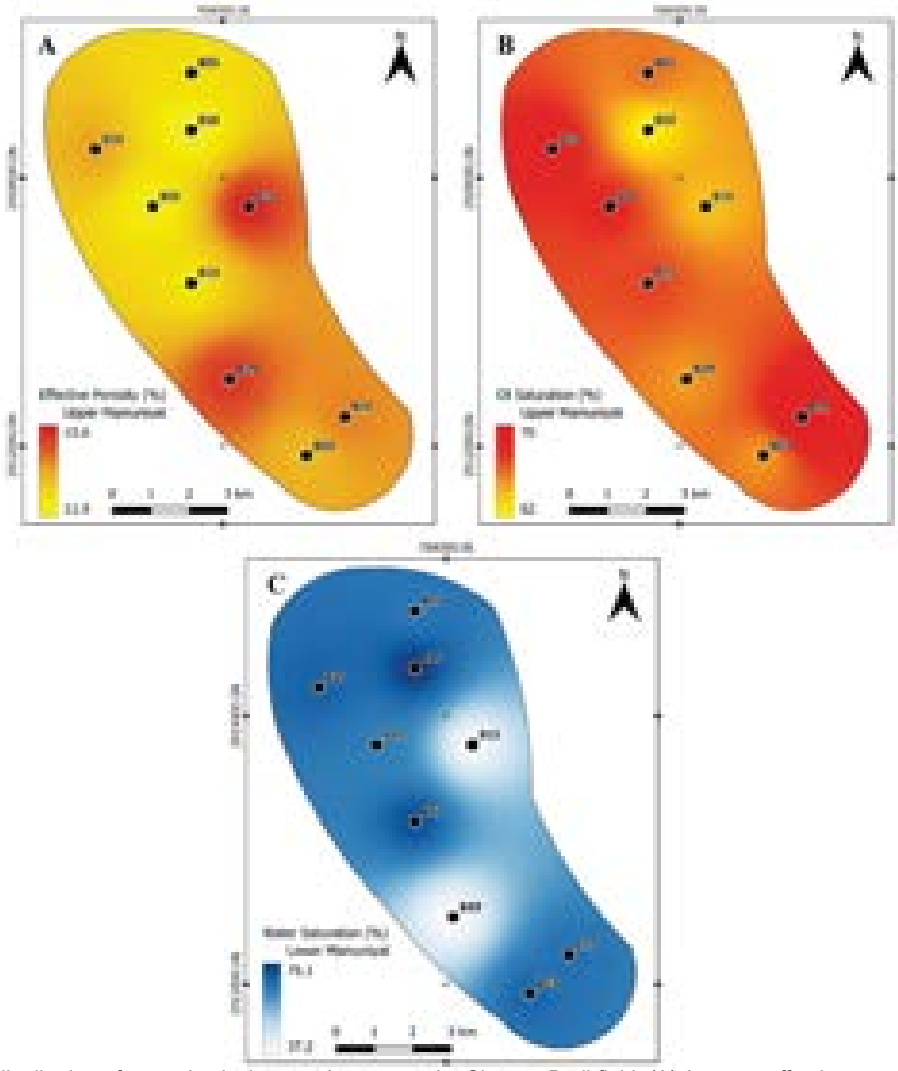


Fig. 6. Spatial distribution of petrophysical properties across the Sharara B-oil field. (A) Average effective porosity (Φe) of the Upper Mamuniyat; (B) Oil saturation (So) of the Upper Mamuniyat; (C) Water saturation (Sw) of the Lower Mamuniyat. The maps demonstrate high reservoir quality and hydrocarbon concentration in the Northwest, contrasted by high water saturation in the Lower member across most of the field.

with unfavorable variables (Vsh, Sw) inverted. Parameters were weighted based on geological significance: Φe (40%), Sw (25%), Vsh (15%), Φt (15%), and H (5%). The HPS was calculated as: HPS = (0.40 × Φe_norm) + (0.25 × Sw_norm) + (0.15 × Vsh_norm) + (0.15 × Φt_norm) + (0.05 × H_norm) Calibration against volumetric indicators (H × So) ensured the index represents recoverable volumes. HPS values above 0.70 correspond to So ≥ 60% and Φe ≥ 12%, while scores below 0.40 indicate water-dominated zones (Sw > 75%).

3D Reservoir Modeling Workflow

The structural framework was developed in Petrel using horizontal cell dimensions of 50 × 50 meters. Recalculated parameters were upscaled to 1-foot intervals while preserving net pay flags at a finer resolution of 0.5 feet. Sequential Gaussian Simulation (SGS) [34] was conducted separately for each reservoir member, with variogram ranges reflecting channel architecture—300 meters horizontally and 5 meters vertically. Model validation at well locations, including a blind-well test at B19, showed deviations below 8%, comfortably within the 15% industry acceptance criterion.

Critical Distinction from Conventional Approaches

This methodology minimizes errors by employing density-based shale-corrected effective porosity (Φe), basin-standard Archie parameters, and strict simultaneous application of cutoff criteria. The workflow complies with industry standards and has been validated against regional petrophysical studies of the Mamuniyat Formation in the Murzuq Basin [18, 25, 35], which confirm the reliability of these thresholds for distinguishing productive net pay in Paleozoic clastic sequences.

Results

All petrophysical parameters were calculated using industry-standard deterministic methods (Figs. 6 and 7). Critical corrections applied to

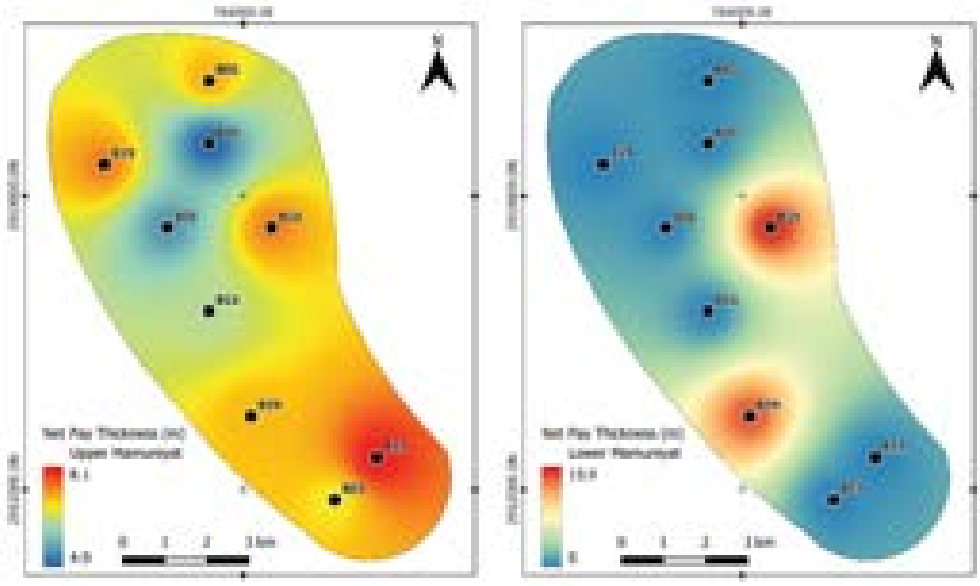


Fig. 7. Net Pay Isopach maps comparing the two reservoir units. (Left) Upper Mamuniyat net pay, showing a consistent and continuous reservoir sheet; (Right) Lower Mamuniyat net pay, illustrating the restricted, localized accumulation in the Northeast. The disparity in pay distribution visually supports the 6.9-fold difference in hydrocarbon volume between the two members.

the dataset include: (1) Φe derived from density logs with mandatory shale correction [Φe = Φt × (1−Vsh)]; (2) Sw calculated using Murzuq Basin calibrated parameters (Rw = 0.08 Ω·m @ 70°C, a = 1.0, m = 2.0, n = 2.0); and (3) the simultaneous application of net pay cutoffs.

Well-by-Well Net Pay Distribution and Oil Saturation

Table 1 presents the verified net pay thickness and oil saturation for all nine wells. The results show that the Upper Mamuniyat consistently contributes to the pay across the field, whereas the Lower Mamuniyat meets the productivity criteria only in structurally elevated locations (specifically Wells B15 and B29). In the other seven wells, the Lower Mamuniyat does not meet the saturation cutoff (Sw ≤ 60%) and is therefore classified as water-bearing.

Comparative Member Statistics and Field Averages

The reservoir exhibits significant internal heterogeneity. Table 2 summarizes the reservoir members, while Table 3 presents field-wide statistics. The Upper Member is identified as the primary target due to its high average oil saturation (So avg. 69%), whereas the Middle Member functions as a regional seal or baffle, characterized by a high average shale volume (24.8%).

Well Ranking and Potential

The Hydrocarbon Potential Score (HPS) was used to rank the wells, as shown in Table 4. This ranking balances rock quality and fluid saturation. Wells B15 and B29 rank highest due to contributions from both reservoir members, while Well B12 stands out as the highest-quality producer from a single member (Fig. 8).

Water Saturation Distribution

Table 4 presents the recalculated water saturation (Sw) values using Murzuq Basin standard parameters (Rw = 0.08 Ω·m @ 70°C, a = 1.0, m = 2.0, n = 2.0) with effective porosity (Φe) derived from density logs. The verified data confirm that the Upper Mamuniyat across all nine wells maintains high oil saturation (Sw = 22.5% – 40.0%), reinforcing its status as the primary reservoir target.

Table 1

Net Pay Thickness (H) and Oil Saturation (So) for All Wells

Well ID	Gross Thickness (m)	Net Pay H (m)	Avg. Φe (%)	Avg. So (%)	Primary Pay Zone
B01	111.0	5.4	12.1%	68.0%	Upper Member
B03	145.0	6.8	13.5%	65.0%	Upper Member
B05	132.5	7.2	12.8%	66.0%	Upper Member
B10	128.0	4.9	11.9%	62.0%	Upper Member
B12	118.5	8.1	14.2%	70.0%	Upper Member
B13	122.0	6.3	12.5%	67.0%	Upper Member
B15	139.5	21.4	15.6%	64.0%	Upper & Lower
B19	115.0	7.5	13.9%	69.0%	Upper Member
B29	126.0	19.8	15.2%	65.0%	Upper & Lower

Table 2

Comparative Statistics of Reservoir Members

Reservoir Member	Avg. Фе (%)	Avg. Vsh (%)	Avg. Sw (%)	Avg. So (%)	HPS	Status
Upper Member	14.8%	12.5%	31.0%	69.0%	0.81	Primary Pay
Middle Member	9.2%	24.8%	82.0%	18.0%	0.26	Non-Commercial
Lower Member	11.4%	18.2%	66.0%	34.0%	0.39	Secondary Pay*

Table 3

Field-Average Petrophysical Parameters Within Net Pay Intervals

Parameter	Minimum	Maximum	Average	Std. Deviation
Eff. Porosity (Фе)	10.0%	22.4%	14.8%	3.1%
Shale Volume (Vsh)	4.0%	30.0%	12.5%	6.5%
Water Sat. (Sw)	22.5%	60.0%	31.0%	8.2%
Oil Sat. (So)	40.0%	77.5%	69.0%	8.2%

In contrast, the Lower Mamuniyat intervals in wells B01, B03, B05, B10, B12, B13, and B19 remain predominantly water-bearing (Sw = 64.2% – 75.1%) and do not meet the saturation cutoff criteria (Sw ≤ 60%), excluding them from net pay calculations. Only the structurally elevated wells, B15 and B29, retain commercial Lower Mamuniyat pay with Sw values of 38.5% and 37.2%, respectively.

Notably, the calibrated model confirms that Well B12 successfully penetrated the Upper Mamuniyat, contributing 8.1 m of high-quality net pay to the field totals.

3D Reservoir Property Distribution

The 3D static model was populated using a Sequential Gaussian Simulation (SGS) algorithm, honoring the updated petrophysical cutoffs and net pay values. The spatial distribution of reservoir properties highlights several critical trends across the field:

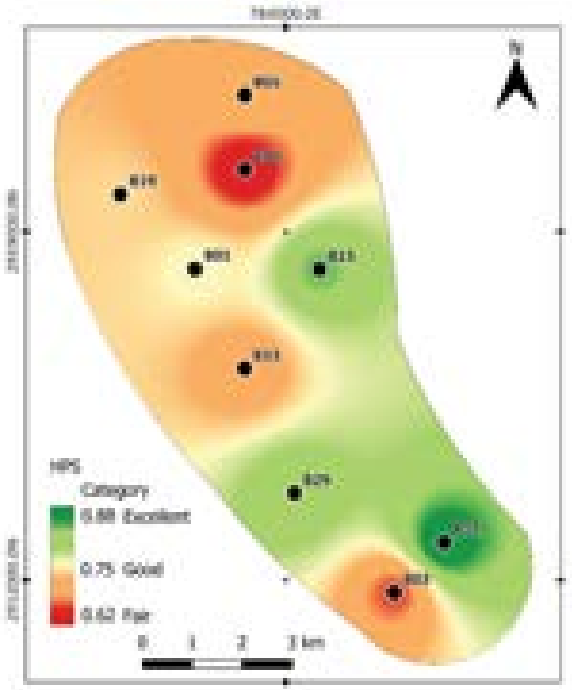


Fig. 8. Spatial distribution of the Hydrocarbon Potential Score (HPS). This integrated map ranks well productivity based on normalized petrophysical parameters. The Northeastern sector (Wells B12, B15, and B29) exhibits the highest potential (HPS > 0.80), identifying it as the primary target for future field development and infill drilling.

Table 4

Ranking of All Nine Wells by Hydrocarbon Potential Score (HPS)

Rank	Well ID	HPS	Primary Driver	Potential
1	B12	0.88	Best So and cleanliness	Excellent
2	B15	0.84	High Net Pay (Dual Zone)	Very Good
3	B29	0.82	High Net Pay (Dual Zone)	Very Good
4	B01	0.76	High Upper So	Good
5	B19	0.74	Consistent Porosity	Good
6	B05	0.72	Moderate Vsh	Good
7	B13	0.69	Mid-range Saturation	Fair
8	B03	0.66	Thickness-driven score	Fair
9	B10	0.62	Lower Porosity Trend	Fair

Effective Porosity (Фе): The Upper Mamuniyat exhibits the most consistent lateral continuity, with values ranging from 12% to 18%. Spatial analysis confirms a significant reservoir quality improvement toward the northeastern sector of the B-Field.

Oil Saturation (So): The saturation model highlights a clear stratigraphic divide. The Upper Member is oil-saturated across the entire structural crest, maintaining an So > 60% across 89% of its net pay intervals. Conversely, the Lower Member pay is strictly localized to the highest structural closures within the B15/B29 block, indicating a deeper oil-water contact (OWC) or a distinct stratigraphic trap for the lower unit.

Net Pay Thickness: The greatest accumulations of net pay are concentrated in the northeastern structural high. For the Lower Mamuniyat, commercial pay is restricted to this high-relief zone, whereas the Upper Mamuniyat pay is distributed more broadly across the structural closure.

Table 5

Water Saturation (Sw) Distribution by Reservoir Member

Well	Upper Member Sw (%)	Middle Member Sw (%)	Lower Member Sw (%)	Status
B01	32.0%	85.2%	64.2%	Upper Pay
B03	35.0%	88.0%	68.5%	Upper Pay
B05	34.0%	84.5%	65.0%	Upper Pay
B10	38.0%	92.1%	75.1%	Upper Pay
B12	30.0%	81.4%	66.8%	Upper Pay
B13	33.0%	89.2%	72.4%	Upper Pay
B15	36.0%	82.0%	38.5%	Dual Pay
B19	31.0%	83.5%	69.2%	Upper Pay
B29	35.0%	80.8%	37.2%	Dual Pay

Model Validation and Uncertainty

All 3D property distributions honor the verified net pay thicknesses established in the well-by-well analysis (Table 1). To ensure model reliability, a blind-well validation was performed; the simulated net pay at well locations deviates by less than 8% from the calculated log values. This level of variance is well within the industry-standard 15% acceptance criterion, confirming that the 3D model is a robust representation of the Mamuniyat reservoir architecture.

The 3D model respects the log-derived petrophysical averages established in this study. While these results remain estimates due to the lack of core data for calibration, the blind-well validation deviation of less than 8% demonstrates that the workflow generates a geologically representative property distribution suitable for development planning.

Critical Findings Summary

Upper Mamuniyat is unequivocally the primary reservoir target in all 9 wells based on So (69.0%)

Lower Mamuniyat pay is restricted to structural highs; elsewhere it is a water-bearing aquifer (Sw > 64.0%).

Middle Mamuniyat is consistently non-commercial and serves as a significant vertical flow baffle (Vsh = 24.8%), which, combined with near-complete water saturation (Sw = 82.0%), effectively compartmentalizes the reservoir units.

Discussion

The integration of three-dimensional petrophysical modeling with rigorously calculated volumetric parameters reveals a reservoir system characterized by significant vertical compartmentalization and lateral heterogeneity within the Mamuniyat Formation of the Sharara B Oil Field. This study emphasizes that a reliable assessment of commercial potential requires explicit integration of net pay determination alongside oil saturation calculations, rather than relying solely on porosity metrics. The methodology employs industry standard effective porosity derivation ($\Phi e = \Phi t \times (1 - Vsh)$) combined with Murzuq Basin calibrated water saturation calculations ($Rw = 0.08\ \Omega \cdot m$). This approach provides a physically consistent framework to distinguish hydrocarbon bearing intervals from water saturated zones, utilizing deterministic reconstruction of Sw from raw resistivity and density logs for wells lacking legacy calculations.

The Upper Mamuniyat is identified as the primary reservoir target based on three key factors. It exhibits superior fluid properties with an average water saturation of 31.0 % and oil saturation of 69.0 %, indicating effective hydrocarbon column preservation above the regional oil water contact. Net pay distribution is consistent across the field, averaging 7.1 meters in thickness, reflecting excellent lateral continuity of productive intervals. Additionally, the Hydrocarbon Potential Score (HPS) averages 0.81, which is the highest among all Mamuniyat members, quantitatively confirming its superior integrated rock fluid properties.

The Lower Mamuniyat serves as a secondary reservoir target with highly localized commercial potential. Despite a greater gross thickness averaging 15.4 meters, its field wide net pay thickness is limited to 2.1 meters after applying consistent cutoff criteria, including effective porosity of at least 10 %, shale volume no greater than 30 %, and water saturation less than or equal to 60 %. Productive intervals are confined to structurally elevated zones in the northeastern field area (B15 and B29), where average oil saturation reaches 74.5 %. In contrast, most wells exhibit minimal or no Lower Mamuniyat net pay due to proximity to the regional oil water contact, resulting in elevated water saturation ranging from 64 to 75 % and effective porosity in non-pay intervals reduced to between 7.9 and 9.8%, falling below the established 10% cutoff. This spatial constraint reflects the dominant influence of structural position on hydrocarbon preservation and is consistent with structurally controlled hydrocarbon retention above a tilted regional oil–water contact (OWC).

The Middle Mamuniyat is consistently non-commercial throughout the field, with average water saturation of 82.0 % and effective porosity of 9.2 %. These values systematically fail to meet net pay criteria, confirming the unit's role as a vertical flow barrier between the Upper and Lower reservoir units. Elevated shale content of approximately 25 %, combined with near complete water saturation, creates an effective baffle that compartmentalizes the reservoir system.

The Hydrocarbon Potential Score (HPS) offers a robust multi criteria index for ranking reservoir quality by integrating normalized values of effective porosity (40 %), water saturation (25 %), shale volume (15 %), total porosity (15 %), and net pay thickness (5 %). Calibration against volumetric hydrocarbon indicators confirms that HPS values above 0.70 consistently correspond to intervals with oil saturation greater than or equal to 60 % and effective porosity greater than or equal to 12 %, while scores below 0.40 indicate water dominated zones. The zonal HPS ranking – Upper 0.81, Lower 0.39, and Middle 0.26 – accurately reflects the reservoir quality hierarchy and distinguishes intrinsic reservoir quality from total volumetric contribution.

A key insight from this study is the quantitative distinction between reservoir quality and volumetric contribution. This principle is quantified through the hydrocarbon column metric (H × So), which accounts for both pay thickness and oil saturation:

Zone	Avg. Net Pay (H)	Avg. Oil Saturation (So)	Hydrocarbon Column (m)
Upper Mamuniyat	7.1 meters	69.0 %	4.90 meters
Lower Mamuniyat	2.1 meters	34.0 %	0.71 meters

This calculation confirms that the Upper Mamuniyat contributes approximately 6.9 times more hydrocarbon volume per well than the Lower Mamuniyat on a field wide basis. The Lower Mamuniyat's contribution is significant only in the restricted northeastern structural high where hydrocarbon column preservation occurs.

Three dimensional modeling reveals critical spatial patterns for development planning. The Sequential Gaussian Simulation (SGS) model honors the verified net pay thicknesses, and blind well validation at B19 showed a deviation of less than 8 %, well within the 15 % industry acceptance criterion. This confirms the model as a robust representation of the Mamuniyat architecture. Commercial potential within the Lower Mamuniyat is limited to the northeastern structural high, while 78 % of the field area contains water dominated intervals in this unit.

These findings support a tiered development strategy. First, prioritize Upper Mamuniyat completions field wide due to consistent pay distribution. Second, selectively target Lower Mamuniyat completions in structurally confirmed sweet spots. Third, treat the Middle Mamuniyat as a flow barrier in reservoir simulations to accurately represent vertical compartmentalization. This methodology provides a reproducible framework for reliable reservoir evaluation in the Sharara B Oil Field and similar data limited settings.

Conclusion

This study offers a petrophysically consistent characterization of the Mamuniyat Formation in the Sharara B-Oil Field using industry-standard parameter calculations and rigorous net pay determination. The evaluation employs density-derived effective porosity ($\Phi e = \Phi t \times [1 - Vsh]$), Murzuq Basin-calibrated water saturation ($Rw = 0.08\ \Omega \cdot m$ at 70°C), and strict simultaneous cutoff criteria ($\Phi e \geq 10\%$, $Vsh \leq 30\%$, $Sw \leq 60\%$). By deterministically reconstructing missing logging data for critical wells, this study ensures a complete and verified field-wide dataset for the first time.

The Upper Mamuniyat is clearly the primary reservoir target, exhibiting superior fluid properties with an average water saturation of 31.0% and oil saturation of 69.0%. It maintains consistent net pay across the field, averaging 7.1 meters in thickness, and achieves the highest Hydrocarbon Potential Score (HPS) of 0.81. In contrast, the Lower Mamuniyat serves as a secondary target with highly localized commercial potential. Its field-wide average net pay thickness is limited to 2.1 meters and is confined to the northeastern structural high (B15/B29), where hydrocarbon column preservation occurs. Outside this structural closure, the Lower Member is predominantly water-bearing, with saturations exceeding 64%. The Middle Mamuniyat is confirmed as non-commercial field-wide, acting as a 15-meter thick vertical flow barrier and baffle.

Volumetric analysis confirms that the Upper Mamuniyat contributes approximately 6.9 times more hydrocarbon volume per well than the Lower Mamuniyat, with average hydrocarbon columns (H × So) of 4.90 meters versus 0.71 meters, respectively. Three-dimensional property distributions were validated through a blind-well test at the B19 location, yielding a deviation of less than 8%, confirming the model's reliability for development planning. This workflow demonstrates that robust reservoir evaluation must integrate volumetric parameters with spatial quality indicators to avoid misclassifying water-bearing intervals, providing a solid foundation for targeted completion strategies in the Sharara B-Oil Field.

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Подяка: Автори висловлюють вдячність анонімному рецензенту та редактору за цінні зауваження й відгуки, що суттєво покращили якість рукопису.
Внесок авторів: Усі автори зробили рівноцінний внесок у розробку концепції та дизайну дослідження, аналіз даних і підготовку рукопису
Конфлікт інтересів: автори засвідчують, що, незважаючи на те, що один із авторів статті є членом редакційної колегії цього журналу, процес рецензування, прийняття рішення щодо публікації та редагування проводилися незалежно, без його участі чи впливу. Будь-які потенційні конфлікти інтересів були повністю усунені шляхом зовнішнього контролю процесу.
Декларація про використання генеративного штучного інтелекту: Автори використовували інструменти генеративного штучного інтелекту (GenAI) для допоміжної роботи: Elicit було залучено для допомоги в перегляді літератури, а QuillBot – для допомоги в редагуванні тексту. Усі результати роботи з цими інструментами були ретельно контрольовані, перевірені та, за необхідності, відредаговані авторами. Автори несуть повну відповідальність за зміст та цілісність публікації.

Acknowledgments: The authors gratefully acknowledge the anonymous reviewer and the editor for their valuable comments and feedback, which significantly enhanced the quality of the manuscript.
Authors Contribution: All authors contributed equally to the study's conception, design, data analysis, and manuscript preparation.
Conflict of Interest: The authors certify that, although one of the authors of the article is a member of the editorial board of this journal, the peer review, publication decision, and editorial processes were conducted independently, without their participation or influence. Any potential conflicts of interest were fully mitigated through external oversight of the process.
Declaration of use of generative artificial intelligence: The authors utilized generative artificial intelligence (GenAI) tools in a supportive capacity: Elicit was employed to assist in reviewing the references, and QuillBot was used to aid in language revision. All outputs from these tools were carefully supervised, reviewed, and, where necessary, edited by the authors. The authors retain full responsibility for the content and integrity of the publication.

Статистичний і 3D-петрофізичний аналіз пластів колекторів і ефективної продуктивної товщі пласта Мамуніят, нафтове родовище Шарара B, басейн Мурзук, Лівія

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АНОТАЦІЯ

У цьому дослідженні представлено комплексний статистичний аналіз і тривимірне (3D) петрофізичне моделювання формації Мамуніят на нафтовому родовищі Шарара B, басейн Мурзук, Лівія. Основною метою є оцінка якості колектора та просторової неоднорідності шляхом інтеграції даних каротажу з геостатистичним моделюванням з використанням петрофізичних методів промислового стандарту. Завдяки чіткій характеристиці ефективної пористості та розподілу флюїдної насиченості, у поєднанні із суворим дотриманням норми чистої продуктивності (Фе ≥ 10%, Vsh ≤ 30%, Sw ≤ 60%), дослідження визначає найбільш перспективні вуглеводовмісні зони та встановлює відтворювану структуру для оцінки колектора в умовах обмеженої кількості даних. На основі кількісного аналізу каротажних даних із дев'яти свердловин була проведена комплексна статистична та 3D-петрофізична характеристика. Ключові методологічні удосконалення включають ефективну пористість, отриману з каротажу щільності з поправкою на глинистість та водонасиченість, розраховану за допомогою параметрів Арчі, відкаліброваних у басейні Мурзук. Для свердловин, у яких відсутні застарілі криві насичення, значення були детерміновано реконструйовані, щоб забезпечити повноту набору даних. Петрофізичні властивості були розподілені в просторі за допомогою послідовного моделювання Гауса в рамках структурно обмеженої 3D-структури, з точністю моделі, підтвердженою валідацією сліпих свердловин. Результати показують виражену вертикальну компартменталізацію в межах формації Мамуніят. Верхній Мамуніят визначено як основний цільовий резервуар, що демонструє чудові властивості флюїду (середній Sw = 31,0%, So = 69,0%), послідовний розподіл чистої продуктивності по родовищу (середня товщина 7,1 метра) і найвищий бал HPS (0,81). Нижній Мамуніят служить другорядним об'єктом з високо локалізованим комерційним потенціалом; його середня корисна товщина продуктивності в масштабі родовища обмежена 2,1 м і приурочена до структурно піднятих зон у блоках B15 і B29, де відбувається збереження вуглеводневої колони. Сім свердловин демонструють мінімальну продуктивність Нижнього Мамуніята через близькість до регіонального нафтово-водяного контакту. Середній Мамуніят є стабільно некомерційним і функціонує як бар'єр для вертикального потоку. Виправлений об'ємний аналіз підтверджує, що Верхній Мамуніят забезпечує приблизно в 6,9 разів більше об'єму вуглеводнів на свердловину, ніж Нижній Мамуніят, встановлюючи його як оптимальну ціль розробки.

ІНФОРМАЦІЯ ПРО СТАТТЮ :

Рукопис надійшов
9 січня 2026

Отримано після рецензування
23 березня 2026

Затверджено до друку
25 травня 2026

Опубліковано онлайн
30 травня 2026

Ключові слова:

формація Мамуніят, характеристика колектора, продуктивність, нафтонасиченість, 3D геостатистичне моделювання, басейн Мурзук, Лівія.

ISSN 2410-7360 (Print)
ISSN 2411-3913 (Online)
Вісник Харківського національного університету імені В.Н. Каразіна Серія «Геологія. Географія. Екологія» 2026 64 С. 109–120
Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology 2026 64 109–120

ГЕОГРАФІЯ | GEOGRAPHY

https://doi.org/10.26565/2410-7360-2026-64-08

UDC 379.85

Development of cultural tourism in the mountainous parts of the Sheki-Zagatala economic region (on the example of Gabala and Oghuz regions)

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ABSTRACT

Problem statement and Purpose. The article examines cultural tourism and its resources that contribute to the development of some types of tourism related to cultural tourism - archaeological, ethnographic, historical and educational tourism in the Gabala and Oghuz regions. The main objective of this study was to examine the cultural potential of the Gabala and Oghuz regions and assess this potential for tourism development. To achieve this goal, theoretical approaches to cultural tourism were reviewed, statistical data on cultural sites, hotels, and transportation from 2015 to 2023 were analyzed, and tourist routes were developed, covering cities and villages with the highest concentrations of archaeological monuments, local cuisine, museums, ethnic festivals, and folk crafts.
Research methods. The study drew on literary sources from various authors, historical and cultural monuments of national and international significance, the legislative framework governing tourism, and statistical data from the State Statistical Committee of Azerbaijan. Systematic, evaluative, and cartographic methods were also employed.
Research results. As a result of the study, it was determined that both regions have great potential for the development of cultural tourism. In comparison with Gabala region, Oghuz region, although has various cultural tourism resources, but these prerequisites are not sufficiently used. Historically, tourists visit Gabala region in the Sheki-Zagatala economic region, which results in the underdevelopment of other regions in the economic region in terms of tourism. The cultural tourism routes we propose will create conditions for the development of cultural tourism in Oghuz region, and like other types, will open up opportunities for the further expansion of this type of tourism in Gabala region.
Conclusion. The samples discovered during archaeological research in the Gabala and Oghuz regions create significant opportunities for the development of archaeological tourism in the area. The use of numerous architectural and historical monuments in these regions for organizing historical and educational tourism will play a decisive role in the future development of this field. The traditional holidays of the ethnic groups living in the Oghuz and Gabala regions, along with local cuisine, and folk crafts such as carpet

ARTICLE INFO

Manuscript received
26 July 2025

Revised manuscript received
21 January 2026

Manuscript accepted
25 May 2026

Available online
30 May 2026

Keywords:

Gabala region, Oghuz region, cultural tourism, architectural and archaeological monuments, ethnic holidays, tourism routes, cultural heritage examples, History and Local History museums, theaters, local cuisine.

In cites: Agakishiyeva Gunesh, Gasimov Jeyhun, Musayeva Gunay, Jabrayilov Emil, Jafarov Sarkhan (2026). Development of cultural tourism in the mountainous parts of the Sheki-Zagatala economic region (on the example of Gabala and Oghuz regions). *Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology*, (64), 109–120. https://doi.org/10.26565/2410-7360-2026-64-08

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weaving, jewelry making, pottery, and blacksmithing, contribute to the development of ethnographic tourism.
Gabala region has been more strongly promoted among local and foreign tourists, and it is appropriate to apply this tool to Oghuz region. Because Oghuz region is not inferior to Gabala and other regions in the Sheki-Zagatala economic region in terms of cultural tourism resources, and it is appropriate to use this potential in the general socio-economic development of Oghuz region, which lags behind in terms of its level of economic development. The fact that automobile transport is the only means of transport in Oghuz region makes the issue of constant repair and restoration of roads relevant. In terms of the development of cultural tourism, it is important to reconstruct inter-village highways of local importance in the Oghuz region, and to further improve modes of transport such as air and railway in the Gabala region.

Introduction. In the scientific literature, great importance is attached to the study of cultural tourism and its resources. Various researchers – X. Matteucci, Ko Cohens, L. Calvi, S. Moretti, I. Smirnov, O. Lubitseva, O.O. Beidik, A.O. Goncharuk, A.V. Gladkey, I.H. Huseynov, N.T. Efendiyeva, Z.T. Imrani, B.A. Huseynova, G.V. Veliyeva, E.A. Ismayilova, Q.Sh. Mammadov, E.F. Yusifov, M.Yu. Khalilov, V.N. Kerimov, G.B. Soltanova, C.A. Mammadov, S.H. Rahimov – have their own approaches to the essence of such concepts as historical and architectural monuments, cultural potential, cultural and historical factors, cultural heritage monuments, cultural tourism objects, historical and cultural monuments, ethnological resources, socio-cultural processes.

X. Matteucci, Ko Cohens, L. Calvi, and S. Moretti studied the development trends of cultural tourism and formulated three concepts for its near future. The authors examined utopian, dystopian, and heterotopian concepts of cultural tourism and concluded that the heterotopian concept provides the most comprehensive interpretation of the future of this sector. They also discussed the potential implications of adopting the heterotopian approach [13].

According to G. Richards, research in the field of cultural tourism is rapidly expanding, particularly in areas such as cultural consumption, cultural motivation, heritage preservation, the economics of cultural tourism, anthropology, and its relationship with the creative economy. The author notes that the primary motivation for tourists in heritage and cultural tourism is the desire to discover, study, experience, and engage with both tangible and intangible cultural values [18]. Approaches highlighted by Richards - such as the shift from tangible to intangible heritage, increased attention to indigenous peoples and other minorities, and the expansion of the geographic scope of cultural tourism research - can be applied in the study regions.

I. Smirnov and O. Lubitseva examined the unique architectural and tourist features of the sacral architecture of Kyiv-Podil, which developed during the Hetmanship period in Ukraine in the 17th-18th centuries. They compared the architectural dominants of the medieval sacral architecture of the Ukrainian Orthodox Kyiv-Podil with the Roman Catholic architecture of Kamianets-Podilskyi (17th-18th centuries), highlighting their significant tourist potential for the development and restoration of Ukraine's tourism industry after the war. The authors emphasized the historical undervaluation of sacral medieval architecture in the Cossack Baroque style – both in terms of tourism development and the education of schoolchildren – illustrating this through examples of destruction during the Soviet era and the potential for restoring cultural memory in independent Ukraine (e.g., the Church of St. Nicholas the Good) [19]. Their approach, which underscores the importance of historical monuments for cultural tourism and educational purposes, is highly relevant to our research. Similarly, using the historical monuments in the study regions to educate local schoolchildren is both appropriate and valuable.

O.O. Beidik and A.O. Goncharuk, in their study of the festival segment of cultural and entertainment tourism highlighted the role of deep ethnocultural traditions and a unique historical past in the development of festival tourism. The authors identified several challenges that hinder the growth of festival tourism - insufficient funding, underdeveloped tourism infrastructure, and inadequate promotion of festivals both domestically and internationally [4]. These issues are also relevant to the Oghuz region, where the present study was conducted.

A.V. Gladkey examined the cultural resources of the Khmelnitsky region, which possesses significant historical and cultural tourism potential, and conducted a SWOT analysis of its cultural heritage [6]. The author's recommendations for developing and creating cultural tourism products, as well as mechanisms for promoting them in domestic and international markets, are applicable to the Oghuz and Gabala regions.

Along with the natural features of the region, cultural heritage monuments have also an important role in choosing the area to visit. In some cases, specific cultural objects, and unique heritage assets are considered a key factor in the

selection of the area by tourists. Cultural tourism selected as a developed type in the classification of tourism includes the following [2].

Gabala region covers 17.5% of the territory of the Sheki-Zagatala economic region with 1.55 thousand km^2, and 17.4% of the total population with 108.9 thousand people. These indicators are 1.08 thousand km^2 (12.2%) and 44.5 thousand people (7.1%) for the Oghuz region, respectively [21].

The industry of the Sheki-Zagatala economic region is mainly based on the production of food, light and partially building materials. The leading sector in the economic region is agriculture, whereas the most important and leading field is tourism. Since the attempts to develop tourism in Sheki-Zagatala economic region are not directed properly, tourism enterprises fail in a short time. The placement of tourism facilities in the forest areas of Sheki-Zagatala economic region and their expansion over time increases deforestation in large areas. Although ecotourism, winter tourism, cultural and historical tourism were developed in Sheki-Zagatala economic region in previous years, however adrenaline tourism will now be a more effective way [7].

It is of great importance to study the cultural tourism of Gabala and Oghuz regions, to identify the factors affecting its development, and to indicate the prospective development directions of various types of tourism related to cultural tourism - archaeological, ethnographic, historical and educational tourism. Gabala region is in first place in the region in terms of economic indicators of tourism. Although Oghuz region has favorable opportunities for the development of cultural tourism, it lags behind all districts in the Sheki-Zagatala economic region in terms of the current state of tourism. In this regard, it is very relevant to explore the cultural tourism opportunities of the Gabala and Oghuz regions, which are distinguished by their mountainous terrain.

Materials and methods. The sources of information included statistical data and information on historical and cultural monuments of national and international significance, which formed the basis for all calculations and tables. The overall methodological framework of the study consisted of the following sequential stages:

- *Software stage*: Analysis of literary sources and the legislative framework, and determination of the object, purpose, and objectives of the study.

- *Information stage*: Collection and processing of statistical data and information on historical and cultural monuments of national and international significance, and creation of a database.

- *Cartographic stage*: Construction of tables based on the processed statistical data and information, and preparation of a map.

The object of the study is the cultural tourism resources of the Gabala and Oghuz regions, including architectural and archaeological monuments, historical and local history museums, ethnic holidays, items of folk crafts and folk art, theaters and local cuisine.

The study uses a systemic method that allows the most effective study of the space of cultural tourism, then an evaluation method that allows identifying the spatial differentiation of cultural tourism resources, as well as a cartographic method that allows identifying cities and villages that actively use their cultural tourism resources in the development of tourism.

Results and discussion. Gabala region is one of the six regions included in the Sheki-Zagatala economic region, bordering the Russian Federation, Guba and Gusar regions in the north, Oghuz and Sheki in the west, Ismayilli in the east, and Agdash and Goychay regions in the south. Oghuz region as an integral part of the Sheki-Zagatala economic region borders the Russian Federation in the north, Sheki in the west and south, and Gabala in the east [15].

In the Sheki-Zagatala economic region, 27.2% of the number of hotels, 50.3% of the number of rooms, 51.3% of the single occupancy, 62.1% of the number of accommodated persons, and 60.9% of the number of overnight stays fall on the share of Gabala region. These indicators are 3.9%; 2.9%; 2.7%; 1.3% and 0.8% for Oghuz region, respectively [24]. Analysis of statistical figures shows a sharp difference in the economic indicators of hotels in Gabala and Oghuz regions and confirms that Gabala region is in 1st place in the region, and Oghuz region is in last place.

In order to ensure the rational use of tourism resources and to promote the components of the natural environment and cultural heritage, the year 2011 was declared the "Year of Tourism" in Azerbaijan by the Decree of the President of the Republic of Azerbaijan dated February 15, 2011. The objectives outlined in the action plan prepared for this purpose were achieved in 2015. From this perspective, the 2015 indicators were used for statistical analysis in the study.

Although an increase was observed in all economic indicators of hotels in the study area in 2015-2023, the highest figures were recorded in the number of accommodated persons and overnight stays. During this period, the number of accommodated persons in Gabala region increased by 13.5 times, and the number of overnight stays increased by 17.8 times (Table 1).

Historical-cultural potential includes a number of cultural-heritage tourism objects, their importance (international or local), degree of use, semantic value, etc. [10].

11.7% of the number of libraries, 11.8% of the number of club institutions, 9.1% of the number

Table 1

Economic indicators of hotels in the study area

Economic indicators	Names of regions					
	Oghuz		Gabala		Sheki-Zagatala	
	Years					
	2015	2023	2015	2023	2015	2023
Number of hotels, units	3	3	9	21	54	77
Number of rooms, units	62	62	196	1079	1072	2144
Single occupancy, space	138	138	503	2611	2583	5090
Number of accommodated persons, people	1095	1606	5909	79823	31280	128455
Number of overnight stays, person-night	1194	1810	7653	136012	51064	223414

Source: Tourism in Azerbaijan. (2024). Statistical yearbook. State Statistical Committee of the Republic of Azerbaijan. Baku. 102 [in Azerbaijani]

Table 2

Economic indicators of cultural sites in the study area

Economic indicators	Names of the regions					
	Oghuz		Gabala		Sheki-Zagatala	
	Years					
	2015	2023	2015	2023	2015	2023
Number of libraries	27	24	27	20	251	205
Number of club establishments	27	21	36	17	261	178
Number of museums	2	2	3	3	21	22
Number of parks	2	2	4	4	19	19
Number of post offices	17	11	30	15	156	120

Source: Regions of Azerbaijan. (2024). Statistical yearbook. State Statistical Committee of the Republic of Azerbaijan. Baku. 845 [in Azerbaijani]

of museums, 10.5% of the number of parks, and 9.2% of the number of post offices fall to the share of Oghuz region in the Sheki-Zagatala economic region. These indicators are 9.8%; 9.6%; 13.6%; 21.1% and 12.5% for Gabala region, respectively [17]. Unlike the economic indicators of hotels, the statistical figures of cultural facilities do not have such large or small shares in Gabala and Oghuz regions (Gabala region has twice greater specific weight only in the indicator of parks).

Although a decrease was observed in all economic indicators of cultural facilities in the study area in 2015-2023, the lowest figures were recorded in the numbers of club institutions and post offices. During this period, the number of club establishments in Gabala region decreased by 2.1 times, and the number of post offices decreased by 2.0 times (Table 2).

In the process of organizing tourism, people strive to get in touch with the rich nature. In addition to the picturesque nature, the aesthetic and historical value of monuments enhances their attractiveness for cultural tourism. The presence of both features determines the development of tourism [8].

In the Sheki-Zagatala economic region, two main types of tourism have developed: ecotourism and cultural tourism. The Shahdag National Park (Gabala and Oghuz regions), Turyanchay State Nature Reserve (Gabala and Oghuz regions), and Gabala State Wildlife Refuge (Gabala region), all established within the economic region, shape its natural and recreational resources and support the development of ecotourism.

The study area has various resources that determine the development of cultural attractions. The cultural tourism resources of the area include architectural and archaeological monuments, museums of history and local lore, ethnic holidays, examples of cultural heritage, theaters and local cuisine.

The historical past of the Gabala region is as rich as its nature. The favorable historical and geographical position of the Gabala region has led to the development of its territory by people since ancient times and, as a result, the creation of rich cultural and historical monuments. More than 90 historical, ethnographic and cultural monuments are protected in the region [20]. 15 km from the center of the Gabala region, between the Garachay and Jovurlu rivers, are the ruins of the ancient city of Gabala. The ancient city of Gabala, which was the capital of Caucasian Albania, was also chosen as a large trade center. The name of this city, which existed for more than 1800 years, is also found in the works of ancient writers. An excursion to the ruins of the city of Gabala is of great interest to tourists. On this excursion, tourists have the chance to see the preserved castle walls and separate parts of the tower [12].

The Mukhas Tower, which is 11.6 m high, 1.5 m thick and consists of 3 floors, is one of the

historical monuments of great importance in terms of tourism development. This tower, which dates back to the 9th-13th centuries, is located near the Mukhas village of the Oghuz region and played the role of a guard post during the historical period [11].

Although no architectural monuments of international importance were recorded in the study area, the ancient city of Gabala is included in the list of archaeological monuments of international importance. Architectural monuments of national importance are concentrated in the villages of Hazra (Gabala region) and Filfili (Oghuz region). Archaeological monuments of national importance predominate in Gabala and Oghuz regions. In Gabala region, these monuments are mainly located in the villages of Savalan, Shafili, Bayramkokhali, Sileyli, Tovla and Dizakhli, and consist of a dwelling and a burial mound. In Oghuz region, a dwelling and a necropolis stand out among the archaeological monuments, located near the city

Table 3

List of archaeological monuments of national importance in the study area

Gabala region			Oghuz region
1. Gavur Castle (Bum village)	19. Soil mound (east of Amili village)	37. Bujaq Piri (Sileyli village)	1. Castle hill (1.5 km east of Oghuz city)
2. Chukhur Gabala settlement (in front of Gabala fortress)	20. Kamaltepe (50 m south of Gabala city gate)	38. Surkhay Fortress (between the Turyanchay and Goychay valleys)	2. Castle ruins (1.5 km east of Oghuz city)
3. Tomb (500 m south of Chukhur Gabala village)	21. Ustajan Castle (southeast of Bayramkokhali village)	39. Shihitapa settlement (between the Turyanchay and Goychay streams)	3. Necropolis (near the city of Oghuz)
4. Kurgan (5 km northwest of Hajialili village)	22. Ustajan Hill (10 km southeast of Bayramkokhali village)	40. Gachag house residence (at the junction of Garachay and Turyanchay)	4. Gala settlement (2 km northeast of Oghuz city)
5. Kilsadag Temple (northeast of Hajialili village)	23. Khyrmantepe settlement (east of Bayramkokhali village)	41. Chakhchakhly settlement (1 km southwest of Yengija village)	5. Necropolis (3 km southeast of the village of Karimli)
6. Yaloylutepe Cemetery (Nij Village)	24. Garatepe (1 km southeast of Sarıhajallı village)	42. Bayramkokha Fortress (east of Zalam village)	6. Castle site (500 m south of Karimli village)
7. Construction of «Gachag evleri» (Savalan village)	25. Kelesh fortress site (south of Sileyli village)	43. Maiden's Castle (3 km east of Zalam village)	7. Necropolis (north of Garabaldir village)
8. Kolatan (5 km south of Savalan village)	26. Topraktepe settlement (500 m south of Tovla village)	44. Castle (3 km southwest of the village of Kurd)	8. Big and Small Fortresses (1 km south of Tarkash village)
9. Bulagli dere settlement (2 km northeast of Savalan village)	27. Khazra wooden shrine (3 km northeast of Bayramkokhali village)	45. Yedditapa settlement (3 km north of Bayramkokhali village)	9. Tikanli reserve settlement (2 km south of Tarkash village)
10. Garaul Tepe (Savalan village)	28. Kabir Mikh settlement (2 km northeast of the village of Tovla)	46. Agjaburun settlement (3 km southwest of Kurd village)	10. Jalut settlement (500 m north of Jalut village)
11. Pirasharyf Castle (Dizakhli village)	29. Galadam (4 km north of Gamarvan village)	47. Necropolis of the Cube Graves (near the village of Yenikand)	11. Pir (500 m north of the village of Jalut)
12. Earthen mound (500 m northeast of Dizakhlı village)	30. Temple area in Gabala city (3 km south of Tovla village)	48. Seyidtala settlement (5 km south of the village of Kichik Pirali)	12. Gavur Castle (2 km north of Khachmaz village)
13. Stone mound (north of Dizakhlı village)	31. Ruins of the circular church (3 km northwest of the village of Amili)	49. Gafarli settlement (3 km south of Kichik Pirali village)	13. Balashu's residence (5 km northeast of the village of Khachmaz)
14. Castle (Vandam village)	32. Necropolis (Shafili village)	50. Stone mound (Sileyli village)	
15. Dashmir settlement (5 km north of Vandam village)	33. Daxaltepe (1 km south of the village of Shafili)	51. Ruins of Beyler village (between Amirvan and Yengija villages)	
16. Gala (Nij village)	34. Earthen mound (1 km north of Shafili)	52. Azakhly mound (Azakhly village)	
17. Yaloylutepe necropolis (south of Nij village)	35. Tomb (1 km north of Shafili)	53. Kharabakand location (2 km southwest of Mammadagali village)	
18. Residence and cemetery (Amirvan village)	36. Ahitapa settlement (500 m northeast of Bum village)		

Source: List of immovable historical and cultural monuments of Azerbaijan, approved by the Resolution No. 132 of the Cabinet of Ministers of the Republic of Azerbaijan dated August 2, 2001.

of Oghuz and in the village of Tarkash (Table 3).

Cultural tourism includes architectural and archaeological monuments, culinary experiences, festivals and events, historical or cultural sites, museums and exhibitions, sightseeing, and religious sites such as temples, churches, and mosques [14].

One of the regions distinguished by its cultural heritage is Oghuz region. In Oghuz region, crafts such as carpet weaving, jewelry, pottery and blacksmithing have been developed and passed down from generation to generation. Local craftsmen weave carpets using natural dyes and intricate patterns. The art of jewelry is based on the preparation of jewelry and decorative items made of silver and gold. In pottery, various containers and decorative items are made of clay using traditional methods and ornaments. In blacksmithing, the preparation of household items and metal products occupies a large place. These mentioned art forms increase the cultural richness of Oghuz and attract tourists to the region.

In Gabala, which belongs to the Shirvan carpet weaving school has been one of the occupations of people since ancient times. One of the branches of "Azerkhalcha" Open Joint Stock Company, established in 2017 for this reason, began operating in Gabala region and produces wool and pile carpets. Although the Gabala branch mainly focuses on weaving Shirvan carpets, carpet varieties are made by the carpet weavers-artists of the Open Joint Stock Company. Aiming to preserve the ancient carpet weaving traditions, the Gabala branch continues its activities to attract the interest of local and foreign tourists.

The organization of the demonstration and sale of carpets and carpet products made in Gabala and Oghuz regions and of great interest to tourists will ensure the attraction them to the area and accelerate the development of cultural tourism.

Extensive work is being carried out to transform the Gabala People's Theater into a state drama theater, which was established in 1964 and has shown small and large-scale works on its stage. The Oghuz People's Theater, which has been operating since 1971, plays a major role in the cultural life of the region, and various performances are presented here.

The Gabala Historical and Local History Museum, which has been operating since May 15, 1980, preserves about 1,400 exhibits of historical and scientific importance. The museum, which has an area of 900 m^2, consists of 13 exhibition halls, a rich scientific library, a picture gallery and an open-air exhibition area of ancient stone monuments. There are also 2 branches of the Gabala Historical and Local History Museum, where archaeological, ethnographic and numismatic materials, folk art samples, ancient manuscripts and printed books are exhibited: the Ismayil bey Gutgashenli Memorial House-Museum and the Martyrs' Memory Museum.

About 4,000 exhibits are exhibited in the Oghuz Historical and Local History Museum, which was established in 1981. The museum, which preserves the history, culture, ethnography and craftsmanship of the area, exhibits found as a result of archaeological excavations are of particular importance. Thus, some of the 168 examples of material culture discovered during archaeological excavations in the region date back to 9-10 thousand years ago, further enriching the museum fund. The corners and halls where examples of coppersmithing, pottery, carpentry and numismatics, textiles, jewelry, clothing and household items are displayed are also of great importance for local and foreign tourists.

Theaters will play a major role in enhancing the cultural worldview of local and foreign tourists coming to Gabala and Oghuz regions, and the History and Local History Museums will play a major role in strengthening their historical memory.

Various ethnic holidays are also considered to be factors affecting the development of cultural tourism. The ethnic composition of the population in both Gabala and Oghuz regions is diverse. In Oghuz region, 10.82% of the total population is Lezgins, 0.20% are Jews, and 0.16% are Udins. In Gabala region, Lezgins account for 13.86% of the total population, and Udins account for 3.27% [5].

Jews also live in Oghuz, one of the regions distinguished by the ethnic composition of its population. The Jewish holiday "Pesakh", which means freedom and spring, is important in terms of tourism development. The holiday "Pesakh" (Nisonu) is held in April, begins with a religious ceremony in the synagogue, and ends with the preparation of a festive table. The following delicacies are essential to the Jewish holiday table: "Mesat" instead of bread, the national dish "Khoyavush", and "Khasurut" made from a mixture of fruits and berries.

Lezgin traditions constitute an important component of ethnic tourism resources of the Gabala region. They settled in villages such as Amirvan, Abrikh, Gamarvan, Kusnet, Yenikand, Dizakhli, Bilikh, Sileyli, Malikli, Yengija, Laza and Bayramkokhali. But in these villages, they live mixed with Azerbaijanis. Villages inhabited only by Lezgins, such as Laza, Gamarvan, Amirvan, etc., have their national costumes, folk groups and national cuisine [9].

The holidays of this people are celebrated in Oghuz and Gabala, which are the regions inhabited by Lezgins. The "Yaran Suvar" holiday, called "Bahar Bayrami" in the Lezgin language,

lasts from March 21 to April 4. On the eve of this holiday, "mel", which means "cleaning", also takes place. During the "Vastrakar" holiday, which is held on the night of March 21 to 22, candles are lit and various delicious dishes are prepared. The "Chichek" holiday, one of the ancient holidays of the Lezgins, is also celebrated with great enthusiasm in rural areas.

The Udins, one of the ethnic peoples living in the Oghuz and Gabala regions, are also distinguished by their holidays. The "Jogulin Askhibay" holiday is held in mid-March and combines the cooking of the national dish "Hasra", people sending shares to each other and singing songs.

Local cuisine also belongs to the cultural tourism resources. Since Gabala region (mainly Bum village) is considered the homeland of chestnut in Azerbaijan, various dishes are prepared from chestnuts here. The dishes specific to Gabala region include chestnut kutab, chestnut halva, local baklava, dasharasi kebab and Hamzali halva made with walnuts, which have attracted the attention of tourists.

Oghuz region is famous for its local cuisine in Azerbaijan. Since the forests of the region are rich in wild fruits, various jams are prepared here: walnut, cranberry, barberry and rosehip jams. Among the dishes specific to Oghuz region are kutab cooked in the Oghuz style - Afar, chikirtmali and minced pilaf, dolma made from linden leaves, which attract local and foreign tourists to the area.

Transport plays a significant role in tourism development. It influences the placement and development of tourism and recreation infrastructure, facilitating the creation of various connections between regions of the country. When assessing a territory's tourism and recreation potential, a region's competence in transportation is particularly important [3].

Although only highways are developed as a means of transport in Oghuz region, automobile, railway and air transport are also distinguished in Gabala region. The movement of high-speed passenger trains on the 309 km long Baku-Gabala route began on March 18, 2023. The seats in the four-carriage and double-decker high-speed passenger trains consist of standard, business and first class. The modern conditions and high-level service created at the railway station create conditions for the short and safe transportation of local and foreign tourists from the capital to Gabala region, as well as to other regions of the Sheki-Zagatala economic region.

Gabala International Airport, which provides transportation of tourists not only to the Sheki-Zagatala economic region and Gabala region, but also to the north-western zone of Azerbaijan in general, has been operating since November 18, 2011. The further expansion of flights between this airport, which has the ability to receive aircraft of any size, along with Baku airport, other local airports of the country - Ganja, Nakhchivan and Lankaran, as well as airports of neighboring countries, will create positive conditions for the development of cultural tourism and ensure safe transportation of tourists.

Of the 1810 km long Sheki-Zagatala economic region's highways, 324 km (17.9%) fall on Gabala, and 202 km (11.2%) on Oghuz. Also, 24 km (66.7%) of the 36 km long first-class highways in the Sheki-Zagatala economic region are concentrated in Gabala [25].

In the region, Sheki and Gabala regions stand out in terms of the length of general highways, including Gabala for I category roads, Sheki for II category roads, Sheki and Gakh for III category roads, Sheki and Gabala for IV category roads, and Balakan for V category roads, 72.2% of general highways in Gabala region, and 65.3% in Oghuz region belong to IV category (Figure 1).

The Ismayilli-Balakan highway of republican importance passes through the territory of both Gabala and Oghuz regions, providing transport connections for many villages of both regions. There are local highways between other villages. The development of cultural tourism will

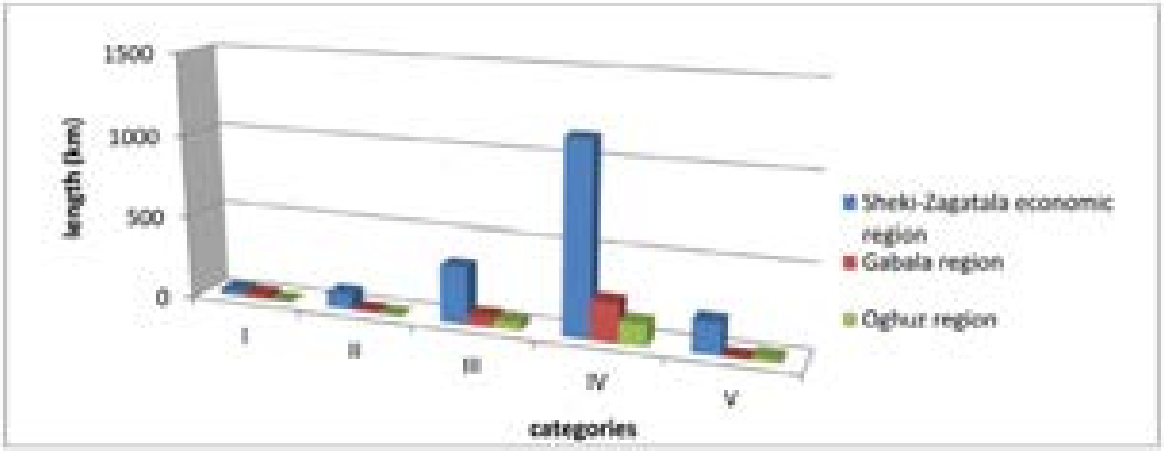


Fig. 1. Distribution of highways by category in the study area

necessitate the reconstruction of inter-village highways of local importance. Unlike Gabala, Oghuz region does not have other modes of transport, so it is advisable to further improve the roads.

The "Archaeological Tourism in Azerbaijan" cultural tourism route - created to promote cultural heritage and encourage the use of cultural assets for tourism purposes, and covering the Gabala, Sheki, Tovuz, Shamkir, and Aghsu regions - the "Five Capitals of Five Eras" cultural tourism route, which encompasses five cities that served as capitals of states that emerged on the territory of Azerbaijan in different historical periods (Ganja, Barda, Shamakhi, Baku, and Gabala), and the "Historical Traces of Ancient Caucasian Albania" cultural tourism route, which aims to popularize the historical and cultural monuments of Caucasian Albania and covers the Gabala, Sheki, and Gakh regions - have all received state status in Azerbaijan. The inclusion of the Gabala region in all three certified cultural tourism routes highlights the state-level attention given to the development of cultural tourism in this region.

The government's efforts to develop tourism in the Gabala region are focused on creating a comprehensive network of tourism infrastructure. Even before Azerbaijan gained independence, a tourist base was established in the Gabala region in 1975 during the Soviet period. After independence, one of the eight tourist information centers created in the country operated in the Gabala region. Today, one of the country's five functioning airports is located in Gabala, and one of the three high-speed passenger train routes in Azerbaijan also connects to this region.

The Gabala region stands out not only within the Sheki-Zagatala economic region but also across Azerbaijan for its level of tourism development. Gabala accounts for 4.0% of the total number of overnight stays in the country and 4.1% of the total number of accommodated persons. In terms of overnight stays, Gabala ranks 5th among the 70 cities and regions of Azerbaijan (after Baku (57.6%), Guba (5.5%), Khachmaz (4.7%) and Naftalan (4.2%) regions). In terms of the number of accommodated persons, the Gabala region ranks 3rd, following Baku (61.4%) and the Guba region (5.8%).

Oghuz region, which is included in the list of backward regions of the region in terms of its level of economic development, has a small population and specializes in the production of agricultural products, and with its rich cultural tourism resources, it is possible to achieve general socio-economic development (nominal income of the population - 147,816 thousand manats, number of employed person - 22,647 people, unemployment rate - 6.9%, average monthly nominal wage - 591.4 manats, number of newly opened jobs - 45 [17]).

The legislative framework for tourism consists of the "State Program for the Socioeconomic Development of Regions of the Republic of Azerbaijan (2019-2023)" and "Strategic Roadmap for the Development of Specialized Tourism Industry in the Republic of Azerbaijan".

The State Program for the Socioeconomic Development of Regions for 2019-2023 in the Oghuz region envisaged the development of various types of tourism, including cultural tourism, major renovations and construction of cultural sites, restoration and conservation of historical monuments, improvement of telecommunications and postal services, construction, reconstruction, and major renovation of local and inter-village roads, as well as the creation of social infrastructure [22]. Since the State Program expired in 2023, most of these measures have already been implemented.

To further increase the tourism potential of the region, tourism activities should not be limited to natural sites. The combination of tourist routes with historical and cultural heritage sites creates more opportunities that are attractive for tourists. For example, ancient monuments, ethnographic villages, historic castles, and architectural examples can be presented as an integral part of tourist packages. This not only increases tourist interest but also creates an additional source of income for the local population [16].

In the "Strategic Roadmap for the Development of Specialized Tourism Industry in the Republic of Azerbaijan", approved by the Decree of the President of the Republic of Azerbaijan dated December 6, 2016, one of the strategic goals is the development of regional tourism types for local and foreign tourists. To achieve the strategic goal, 5 priorities are envisaged, one of which is the creation of cultural tourism routes [23].

Since the measures to be taken to create routes include the promotion of new tourism routes, it is very important to prepare automobile and pedestrian routes for the cultural tourism resources of the study regions. In Gabala region, it is proposed to prepare cultural tourism routes like Gabala city-Hamzali-Bum-Gamarvan, Shafili-Sarıhajalli-Dizakhli-Chukhur Gabala and Yenikand-Zalam-Kichik Amili-Boyuk Amili-Hajialili, and in Oghuz region, it is proposed to prepare cultural tourism routes like Padar-Karimli-Garabaldır, Oghuz city-Jalut-Mukhas and Khachmaz-Abdallı-Filfili. During these cultural tourism routes that we propose and will cover both research regions, it is possible to get acquainted with local cuisine (Hamzali and Bum villages), History and Local History museums (Gabala and Oghuz cities), archaeological and architectural monuments, ethnic holidays and various folk crafts (Figure 2).

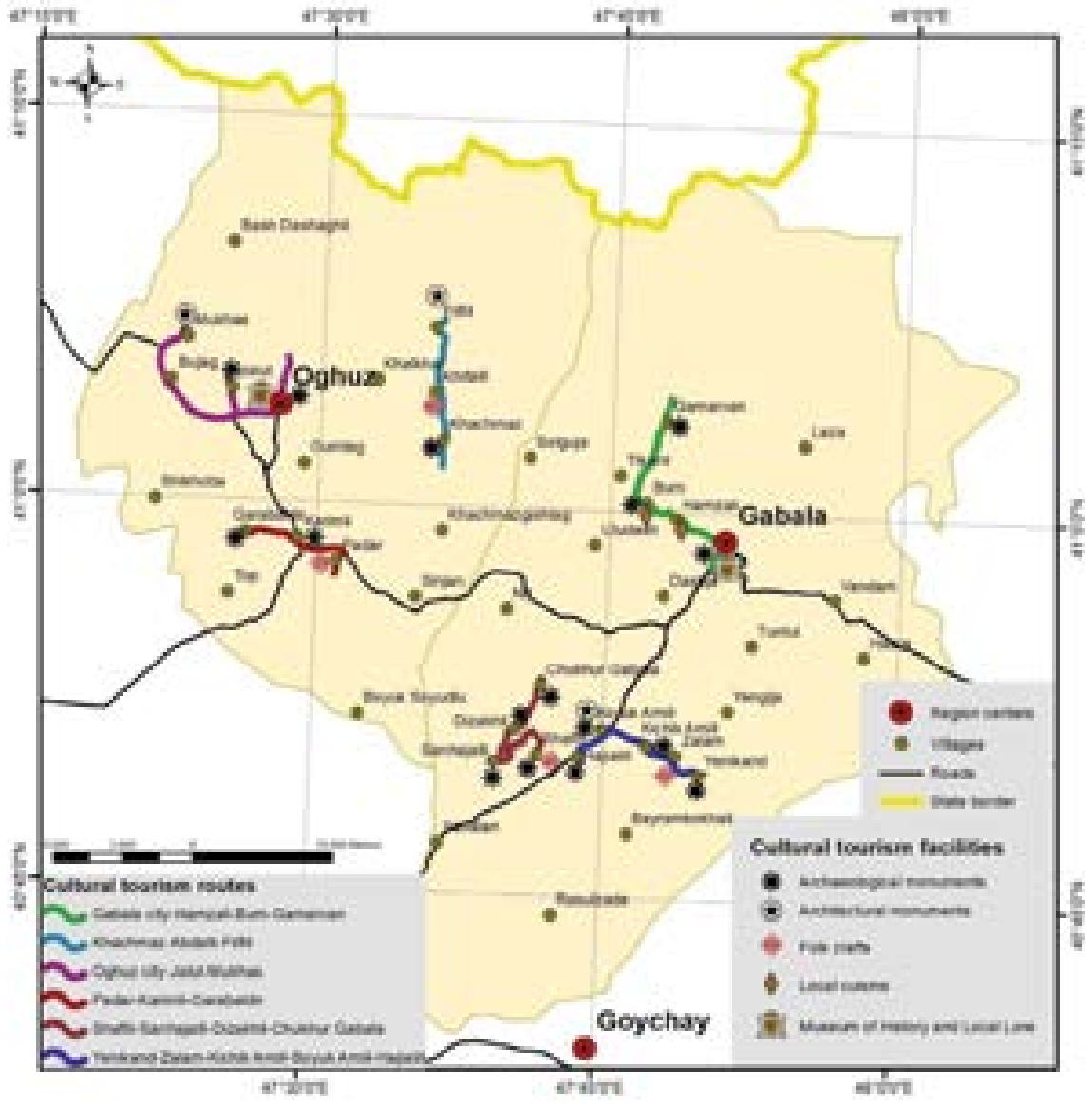


Fig. 2. Map of cultural tourism routes in the study area

It is planned that two of the 3 cultural tourism routes prepared for Gabala region (Gabala city-Hamzali-Bum-Gamarvan and Yenikand-Zalam-Kichik Amili-Boyuk Amili-Hajialili) will be implemented on roads of republican importance and one (Shafili-Sarıhajalli-Dizakhli-Chukhur Gabala) will be implemented on local roads, and two of the 3 cultural tourism routes prepared for Oghuz region (Oghuz city-Jalut-Mukhas and Khachmaz-Abdallı-Filfili) will be implemented on local roads and one (Padar-Karimli-Garabaldır) will be implemented on roads of republican importance.

The strengthening of socio-cultural processes, the emergence of cultural values change the norms and habits of consumption of services, the choice of services, determined in the field of tourism and recreation. Interest in other cultures gives rise to the desire to travel and get new experiences, which is manifested in the formation of various products of enterprises of the tourist and recreational complex. Raising the cultural and educational level of the population leads to understanding the experience of other countries and regions and developing ways to use it in their professional activities [1].

Conclusions

1. The Sheki-Zagatala economic region ranks second in Azerbaijan, after the Baku economic region, in terms of ethnic diversity. This diversity is reflected in the distinct lifestyles and traditions of its small ethnic groups, which attract the interest of tourists visiting the region. While the ancient history of both regions positively influences their cultural tourism potential, the Gabala region possesses a particularly ancient past. The city of Gabala has even been compared to such ancient and renowned cities as Babylon, Troy, Pompeii, and Carthage.

2. The relatively weak development of tourism in the Oghuz region is associated with its level of socioeconomic development, the scale of construction activities, and the development of transport and other infrastructure sectors. However, several national policies are aimed at supporting tourism development in the Oghuz region, including the "Law on Tourism, " approved by the Decree of the President of the Republic of Azerbaijan dated December 27, 2021; the "State Program for the Development of Tourism in the Republic of Azerbaijan for 2010-2014, "approved by the Presidential Decree dated April 6, 2010; and the "State Program for the Socioeconomic Development of Regions (2019-2023)".

3. Gabala is the fastest-developing region within the Sheki-Zagatala economic region. In Gabala, which demonstrates a high level of socioeconomic development by Azerbaijani standards, numerous light industry and food processing enterprises have been established in recent years. These include lemonade and piano factories, dairies, grape and hazelnut processing plants, canning factories, bakeries, grain elevators, brick factories, and concrete plants. Although the Oghuz region is considered one of the most economically underdeveloped areas within the economic region, its rich cultural and tourism resources offer significant potential for overall socioeconomic development. The Oghuz region could also be incorporated into the "Historical Traces of Ancient Caucasian Albania" cultural tourism route, one of the three certified routes in Azerbaijan. The presence of historical monuments dating back to the period of Ancient Caucasian Albania further strengthens this potential.

4. In addition to the cultural tourism routes currently developed in Azerbaijan - "Archaeological Tourism in Azerbaijan", "Five Capitals of Five Eras", and "Historical Traces of Ancient Caucasian Albania" all of which cover the Gabala region - we propose developing three additional cultural tourism routes for each of the study regions. In Gabala region, it is proposed to prepare cultural tourism routes like Gabala city-Hamzali-Bum-Gamarvan, Shafili-Sarıhajalli-Dizakhli-Chukhur Gabala and Yenikand-Zalam-Kichik Amili-Boyuk Amili-Hajialili, and in Oghuz region, it is proposed to prepare cultural tourism routes like Padar-Karimli-Garabaldır, Oghuz city-Jalut-Mukhas and Khachmaz-Abdallı-Filfili. Within the framework of these proposed routes, visitors could experience the majority of the regions' cultural tourism resources, including local cuisine, historical and local history museums, archaeological and architectural monuments, ethnic holidays, and various folk crafts.

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Внесок авторів: всі автори зробили рівний внесок у цю роботу
Конфлікт інтересів: автори повідомляють про відсутність конфлікту інтересів
Декларація про використання генеративного штучного інтелекту: автори підтверджують, що під час підготовки рукопису не використовувалися інструменти штучного інтелекту.

Authors Contribution: All authors have contributed equally to this work
Conflict of Interest: The authors declare no conflict of interest
Declaration of use of generative artificial intelligence: The authors confirm that no AI tools were used during the preparation of the manuscript.

ISSN 2410-7360 (Print)
ISSN 2411-3913 (Online)
Вісник Харківського національного університету імені В.Н. Каразіна Серія «Геологія. Географія. Екологія» 2026 64 С. 109–120
Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology 2026 64 109–120

Розвиток культурного туризму в гірських районах Шекі-Загатальського економічного регіону (на прикладі Габалинського та Огузького районів)

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АНОТАЦІЯ

У статті розглядається культурний туризм та його ресурси, що сприяють розвитку деяких видів туризму, пов'язаних з культурним туризмом – археологічного, етнографічного, історико-пізнавального в Габалинському та Огузькому районах. Основною метою цього дослідження було вивчення культурного потенціалу Габалинського та Огузького районів та оцінка цього потенціалу для розвитку туризму. Для досягнення цієї мети було розглянуто теоретичні підходи до культурного туризму, проаналізовано статистич=і дані про культурні об'єкти, готелі та транспорт з 2015 по 2023 рік, а також розроблено туристичні маршрути, що охоплюють міста та села з найбільшою концентрацією археологічних пам'яток, місцевої кухні, музеїв, етнічних фестивалів та народних ремесел. У дослідженні використано літературні джерела різних авторів, історичні та культурні пам'ятки національного та міжнародного значення, законодавчу базу, що регулює туризм, та статистичні дані Державного комітету статистики Азербайджану. В результаті дослідження було визначено, що обидва регіони мають великий потенціал для розвитку культурного туризму. Порівняно з Габалинським районом, Огузький район, хоча й має різноманітні ресурси культурного туризму, але ці передумови використовуються недостатньо. Історично склалося так, що туристи відвідують Габалинський район у Шекі-Загатальському економічному районі, що призводить до нерозвиненості інших районів економічного регіону з точки зору туризму. Запропоновані нами маршрути культурного туризму створять умови для розвитку культурного туризму в Огузькому районі та відкриють можливості для подальшого розширення цього виду туризму в Габалинському районі. Використання численних архітектурних та історичних пам'яток у цих регіонах для організації історико-пізнавального туризму відіграватиме вирішальну роль у майбутньому розвитку цієї галузі. Традиційні свята етнічних груп, що проживають в Огузькому та Габалинському районах, поряд з місцевою кухнею та народними ремеслами, такими як килимарство, ювелірне мистецтво, гончарство та ковальство, сприяють розвитку етнографічного туризму. Оскільки Огузька район не поступається Габалі та іншим регіонам Шекі-Загатальського економічного району за ресурсами культурного туризму, і доцільно використовувати цей потенціал у загальному соціально-економічному розвитку Огузької района, яка відстає за рівнем економічного розвитку.

ІНФОРМАЦІЯ ПРО СТАТТЮ :

Рукопис надійшов
26 липня 2026

Отримано після рецензування
21 січня 2026

Затверджено до друку
25 травня 2026

Опубліковано онлайн
30 червня 2026

Ключові слова:

Габалинський район, Огузький район, культурний туризм, архітектурні та археологічні пам'ятки, етнічні свята, туристичні маршрути, приклади культурної спадщини, історико-краєзнавчі музеї, театри, місцева кухня.

https://doi.org/10.26565/2410-7360-2026-64-09

UDC 502; 574 /47. 9245/ 911.3

The impact of natural and anthropogenic risks on population safety and agriculture development in the Gazakh-Tovuz economic region

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ABSTRACT

The natural-geographical conditions of the Gazakh–Tovuz economic region determine the spatial interdependence between population safety and agricultural development. However, global climate change, land degradation, increasing environmental pressure, and the expansion of human activity have significantly increased vulnerability to natural and anthropogenic risks. At the same time, agriculture remains a key sector of the regional economy, playing an important role in employment. Uneven spatial development, declining land productivity in some areas, and increasing exposure to natural hazards hinder the efficient use of resources. This situation highlights the need for a comprehensive assessment of risk factors influencing both agriculture and settlement structure. Therefore, identifying the current problems and ensuring sustainable territorial development under changing environmental conditions is of high scientific and practical importance for the region.

Aim of the study. To study the spatial analysis of the Gazakh–Tovuz economic region and the role of natural-anthropogenic risks in the territorial organization of agriculture and the safe settlement of the population. To determine the level of disaster risk in the development of agricultural sectors. This makes it possible to assess the impact of natural and anthropogenic risks on both population safety and the sustainable development of agricultural areas in zones highly sensitive to destructive processes within the study area.

Research methodology. This study applies a quantitative approach to analyze the impact of natural and anthropogenic risks on population settlement and agricultural development. The assessment is based on an integrated index system that considers the intensity and frequency of events, the level of exposure, and the vulnerability of agricultural systems. In addition, the Analytic Hierarchy Process is used to rank different types of risks through a weighted multi-criteria evaluation. The results support the identification of vulnerable areas and the development of spatial risk maps for the region.

Results. The spatial analysis indicates that natural and anthropogenic risks in the Gazakh–Tovuz economic region are unevenly distributed and significantly influence both population settlement patterns and agricultural development. The southern and western parts of the region are identified as the most vulnerable zones, particularly where agricultural activity is more intensive and settlements are more exposed. Based on a four-level classification, approximately 0–5% of the territory is classified as very weak risk, 10–20% as weak, 20–33% as medium, and 33–50% as strong risk. Weak-risk areas have limited impact on settlements and agriculture, while medium and strong-risk zones are associated with recurring damage to infrastructure, agricultural lands, and rural settlements, leading to socio-economic disruptions. Overall, a considerable part of the region is exposed to medium and high risk levels, which adversely affects the stability of settlement systems and the sustainable development of agriculture.

ARTICLE INFO

Manuscript received
1 May 2025

Revised manuscript received
10 March 2026

Manuscript accepted
25 May 2026

Available online
30 May 2026

Keywords:

agriculture, risk assessment, population safety, economic and geographical assessment, continuous development, Gazakh-Tovuz economic region.

Introduction

Population growth, increasing anthropogenic impacts, and climate change in the Gazakh-Tovuz economic region intensify natural and anthropogenic risks, leading to a reduction in usable land resources and negatively affecting agriculture. These processes also influence population safety and the spatial organization of economic activities. Therefore, reducing risks

In cites: Alakbarova Samira (2026). The impact of natural and anthropogenic risks on population safety and agriculture development in the Gazakh-Tovuz economic region. *Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology*, (64), 121–130. https://doi.org/10.26565/2410-7360-2026-64-09



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and implementing protective measures are of crucial importance. Natural and anthropogenic risks cause serious damage to settlements, infrastructure, agricultural areas, and natural resources, leading to considerable economic losses. Therefore, studying these risks and implementing mitigation measures is of great importance.

This topic is relevant because agriculture plays a crucial role in the Gazakh-Tovuz economic region, serving as a primary source of employment and income for a significant part of the population. Analyzing the impact of natural and anthropogenic risks on population safety and agricultural development is essential for identifying problems, improving the use of resources, and ensuring sustainable development. Furthermore, the analysis of the spatial distribution and intensity of natural and anthropogenic risks, as well as their potential impacts, provides an important foundation for ensuring sustainable regional development and effective spatial planning.

The purpose of the research work. The main purpose of this study is to comprehensively analyze the impact of natural and anthropogenic risks on population safety and agriculture development in the Gazakh–Tovuz economic region, while assessing future development prospects and potential risks. The research also evaluates the effects of these factors on the agricultural sector and determines the overall level of risk. Based on these assessments, the study aims to develop scientifically grounded strategies to enhance the resilience of the region's agriculture sector, reduce risks, and support sustainable socio-economic development, thereby improving the welfare of the rural population.

Material and methods

Within the framework of the study, methods including risk assessment, mapping, forecasting, geographic information systems, and Analytic Hierarchy Process (AHP) analyses were applied. Furthermore, the decisions and measures outlined in State Programs were thoroughly analyzed, and the results were presented based on extensive scientific literature. This study applies two complementary approaches. First, mathematical-statistical methods – based on probability theory are used for parameter estimation, spatial correlation, areal analysis, and landscape structure analysis. Second, mathematical analysis of statistical data – is employed for practical processing of empirical data, including descriptive statistics, spatial distribution analysis, and model fitting. Together, these approaches ensure a robust theoretical-statistical framework and systematic analysis of spatial data.

The study is based on official statistical data, regional development reports, and thematic map covering the Gazakh–Tovuz economic region. Quantitative analysis was applied to assess the impact of natural and technogenic risks on population safety and agricultural development. A hazard-based index approach was used, integrating indicators of intensity, frequency, exposure, and vulnerability to evaluate risk levels. In addition, the Analytic Hierarchy Process (AHP) was applied to rank different risk factors using a weighted multi-criteria system. Spatial analysis and modern computer technologies were used to develop risk map and identify vulnerable zones. The assessment was carried out across different administrative districts to ensure comparative analysis and spatial differentiation of risk levels.

Scientific novelty of the study. It is based on the integrated assessment of natural and anthropogenic risks in the Gazakh–Tovuz economic region using a spatially differentiated approach that combines demographic, population safety, geographical, and agricultural indicators. The regional risk structure is systematically analyzed in relation to settlement patterns and agricultural development, which enables the identification of medium and high-risk zones affecting rural sustainability.

Analysis and Discussion. The Gazakh-Tovuz economic region, located in the western part of Azerbaijan, is distinguished by its rich natural resources, favorable climatic conditions, and strategic geographical position [14]. Agriculture holds an important place in the region's economic structure and is considered one of the main sectors of employment for the population. In particular, traditional activities such as viticulture, grain farming, livestock breeding, and horticulture play a significant role in the socio-economic development of the region. At the same time, the development of agriculture in this region is closely linked to population settlement patterns, since the spatial distribution of settlements, the rural demographic structure, and the availability of labor resources play a decisive role in shaping land use practices and the organization of agriculture. In areas with favourable natural and climatic conditions, agriculture becomes a key determinant of settlement structure and labour allocation.

The structure of land-use distribution in the region plays a decisive role in shaping its agricultural productivity and spatial development potential [13]. Variations among arable land, forest areas, water-covered territories, and other land categories determine both the region's resource availability and its environmental constraints (Fig. 1).

Over the past decade, intensive anthropogenic activities have significantly altered the natural landscapes of the region, leading to a considerable

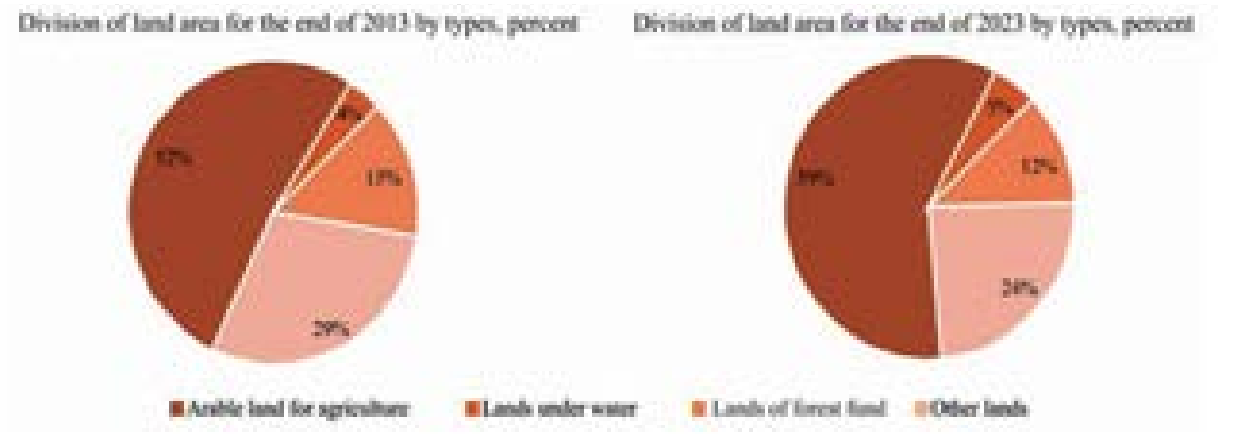


Fig. 1. Division of land area by types in the Gazakh-Tovuz economic region, %
Source: Calculated and compiled by the author using statistical data [16, 21].

reduction in forest cover. As a result of ecological imbalance, certain areas have experienced ecosystem degradation and have become ecologically stressed.

In agriculture, the greatest damage from various natural disasters is caused to soil resources. U. Aksoy [1], Z. Imrani et al [8], N. Korohoda, T. Kupach [10], and others have examined the technological features of evaluating agricultural ecosystem services, while O. Rybalova et al [18] and other foreign researchers have conducted risk assessments for public health due to soil contamination at solid waste disposal sites, carried out large-scale studies in various regions, and obtained scientifically significant innovations. L. Moldavan et al. [15] systematically analyzes the impacts of climate change on the agricultural sector at a macro level and establishes the scientific and theoretical foundations for transitioning to a sustainable development model, O. Kukhar et al. [11] provides a micro-level, analytical evaluation of how diversification strategies enhance the economic resilience of agricultural enterprises and mitigate sustainability-related risks. N. Shevchuk [20], Baranovskyi M., Hlushko D. [7] employed a combination of monographic, comparative, empirical, and abstract-logical methods to systematically evaluate the impacts of climate change on agriculture the scientific foundations for transitioning to a sustainable development model. N.A. Babakhanov [6], R.N. Mahmudov [12], S.G. Rustamov [17], S.A. Tarikhazar et al. [22, 23, 24, 25] and other local specialists have investigated the relief characteristics of the mountainous and foothill areas of Azerbaijan, examined the influence of natural conditions, climate, and the hydrological environment on the development of agricultural sectors, and assessed the formation of extreme and destructive natural events as well as technogenic hazards. The research conducted by us integrates various approaches to perform a comparative analysis, highlights the current status of agricultural development in the Gazakh-Tovuz economic region of Azerbaijan, and relates it to global trends, including prospects and risk assessment.

Especially mudflows cause erosion of soil cover, washing away its valuable topsoil and carrying away stones, clay, sand, etc., this leads to clogging of the soil with suspended matter and its exclusion from crop rotation. Periodically observed mudflows on the rivers of the region, such as Aghstafachay, Akhinjachay, Tovuzchay, Zayamchay, Asrikchay, Shamkirchay and their tributaries, cause lands in the area to become unusable [2, 3]. As a result of mudflows, more than 0.5 thousand ha of the entire land mudflows of the region were washed away and lost 30-40% of their productivity [9, 16]. 3.2% of such lands are located in areas prone to waterlogging. Of the lands taken out of turnover as a result of mudflows, 317 thousand ha were washed away as a result of mudflows in the region [16]. Based on the conducted research, we prepared a diagram illustrating the relationship between the recurrence of natural disaster events and the agricultural damage they caused in the Gazakh–Tovuz economic region during the period from 1950 to 2025 (Fig. 2.).

As a result of various natural disasters, especially mudflows, which occur annually in this district, the total yield of all types of crops is decreasing, and the fields are often flooded. The table demonstrates a clear relationship between the recurrence of natural disaster events in the Gazakh–Tovuz economic region and the magnitude of economic losses in the agricultural sector. In particular, more frequent events are associated with substantially higher damage expressed in manat, indicating an increasing economic burden on agricultural areas and underscoring the necessity of strengthening risk reduction and adaptive management strategies.

Application of the Analytic Hierarchy Process for risk evaluation. The Analytic Hierarchy Process (AHP) was applied in this study

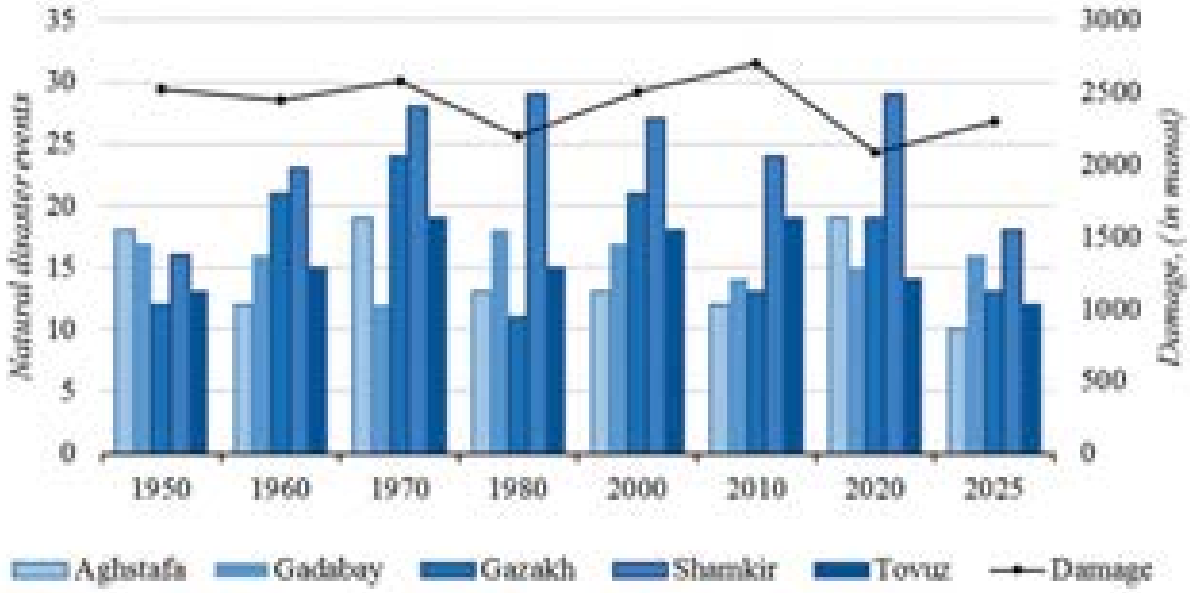


Fig. 2. Recurrence of natural disaster events in the Gazakh–Tovuz economic region and the damage they cause to agricultural areas (in manat)
Source: Calculated and compiled by the author using statistical data [16].

to assess the impact of various natural disaster events and intensive anthropogenic activities on agriculture in the Gazakh-Tovuz economic region [4;]. The method allows evaluating the impact of each event based on a multi-criteria assessment [5, 16, 19].

Three main criteria were defined to evaluate the impact of each disaster event: Severity S_i – the damage caused by the event to agriculture; Frequency F_i – the number of occurrences of similar events within a certain period; Population Affected P_i – the number of people adversely affected by the event. Weights c_S, c_F and c_P were assigned to the criteria based on expert evaluation. In this study, the weights were determined as: $c_S=0.4$, $c_F=0.3$, $c_P=0.3$. The sum of all weights equals 1: $c_S + c_F + c_P = 1$.

The AHP score for each event, including both natural disasters and anthropogenic incidents, is calculated as the weighted sum of the criteria (a):

$$AHP = c_S \text{ x } S_i + c_F \text{ x } F_i + c_P \text{ x } P_i \quad (a)$$

Thus, the AHP score for each disaster event is determined and recorded in the corresponding table. A higher AHP score indicates a greater impact on agriculture and is used to prioritize mitigation measures and plan strategic interventions. Each criterion was scored on a scale from 1 to 5 (Table 1).

The AHP results indicate that certain natural disasters and intensive anthropogenic activities exert a more pronounced negative impact on agricultural development in the region. These prioritized factors highlight the areas where risk mitigation and management measures should be strengthened to reduce potential losses and support sustainable agriculture. Building on this framework, agricultural insurance has increasingly supported the reduction of losses caused by natural and anthropogenic risks and has strengthened the adaptive capacity of rural areas.

Over the period 2000–2025, the agricultural insurance system in Azerbaijan has evolved as an integral component of regional development policy, aimed at improving rural livelihoods and ensuring the sustainable development of agriculture. In this context, insurance contributes to the spatial stability of agricultural systems and the socio-economic sustainability of rural settlement in regions such as Gazakh–Tovuz. The regulatory framework established in 2002 laid the institutional foundation for risk management in agriculture, while subsequent regional programs, particularly the 2019–2023 State Program, further emphasized insurance expansion as a tool for stabilizing rural incomes and enhancing resilience [21]. Thus, the integration of insurance mechanisms into regional development policy plays a significant role in enhancing the resilience and territorial sustainability of agriculture.

Risk assessment. Disaster risk assessment in the agricultural sector is a multidimensional process that requires the integration of hazard characteristics, exposure levels, and system vulnerability. In this study, we applied a hazard index–based methodology to quantitatively evaluate potential risks to agricultural production across different zones. The assessment was conducted in three sequential stages: estimation of the initial hazard index, computation of the agricultural impact index, and integration of both indices to derive the total agricultural risk.

Table 1

Prioritized AHP assessment of the most damaging various natural disaster events and intensive anthropogenic activities on agriculture in the Gazakh-Tovuz economic region (2009-2025)

Date	Location, rivers	Agricultural hazard impact	AHP
04.08.2009	Tovuz, Aghstafa	A severe landslide led to significant damage to agricultural land and private property.	4.4
06.08.2009	Tovuz, Tovuzchay	A landslide destroyed houses and caused partial damage to additional residential properties, resulting in a temporary interruption of agricultural.	3.7
17.05.2010	Amirvar, Gushchu, Zaylik, Shamkirchay	A landslide inflicted substantial damage to farms and resulted in losses, livestock lost.	4.6
28.05.2011	Gadabay, Soyudlu	A landslide caused one human casualty, as well as damage to property and farmland.	3.0
30.05.2014	Agbashlar, Zayamchay	Heavy rainfall caused temporary disruption to agricultural, flooding agricultural fields.	2.5
13.06.2014	Galakand, Shamkirchay	Intense rainfall and mudflows affected residential areas and farm plots, damaging property and crops.	3.7
17.06.2016	Shakerbey, Chetindara, Zayamchay	Severe mudflows resulted in extensive damage to private property, flooding agricultural fields, losses of livestock and poultry were recorded.	3.7
12.06.2020	Yanigly, Meshadili, Alakol, Zayamchay	The landslide caused damage to homes and electrical infrastructure, and flooding agricultural fields.	3.0
18.09.2021	Yanigly, Cirdakhan, Zayamchay	Mudflows damaged approximately 100 hectares of farmland and affected residential walls.	3.7
23.06.2023	Gazakh, Cogazchay	Heavy rain caused the Cogaz river to overflow, resulting in the flooding of farm plots.	3.5
16.05.2024	Ashagı Salahlı and Orta Salahlı villages	Significant damage was inflicted on household farms and agricultural lands.	3.8
26.05.2024	Gazakh, Agstafachay, Cogazchay	Intense rainfall and mudflows caused damage to farmland, with water inundating the land, as a result, damage was inflicted on houses, household plots, agricultural fields, and losses of livestock recorded.	4.8
14.05.2025	Tovuz, Ahmadabad village	Heavy rainfall and hail lasting 10–15 minutes caused significant damage to crop fields and fruit trees. Road transport was disrupted due to difficult driving conditions, and temporary interruptions in electricity supply were recorded.	4.1

Source: The table developed, by S.O. Alakbarova, using data from the State Statistics Committee, the Ministry of Emergency Situations, State Programs, field research, and relevant publications.

Initial hazard ındex: The initial hazard index *(RI)* quantifies the likelihood and severity of natural hazards affecting agricultural areas. It is expressed as a product of hazard intensity and frequency, exposure and vulnerability (b):

$$RI = H \times E \times V \quad (b)$$

Where, *(H)* represents the intensity and occurrence frequency of natural hazards, *(E)* denotes the degree of exposure of agricultural lands and infrastructure, *(V)* indicates the susceptibility of crops and farming systems to the impacts of hazards. Historical disaster records, land-use maps, and environmental parameters were analyzed to accurately determine these variables for each agricultural zone. This approach allows for a spatially explicit assessment of potential hazard levels and the identification of high-risk areas.

Agricultural ımpact ındex: The agricultural impact index *(AI)* assesses the potential consequences of hazards on crop production, accounting for both quantitative and qualitative aspects of agricultural systems. The index is defined as (c):

$$AI = Y \times A \times T \quad (c)$$

Where, *(Y)* represents crop yield, *(A)* denotes the cultivated area, *(T)* is the technology and management index, reflecting the effectiveness of agronomic practices, infrastructure, and adaptive capacity. By incorporating the technological and managerial dimension, the AI index provides a realistic estimate of agricultural losses under hazardous conditions, allowing for the differentiation between zones with similar exposure but varying resilience.

Total agricultural risk: The overall agricultural risk *(TR)* integrates the hazard index with the agricultural impact index, thereby providing a comprehensive measure of risk that

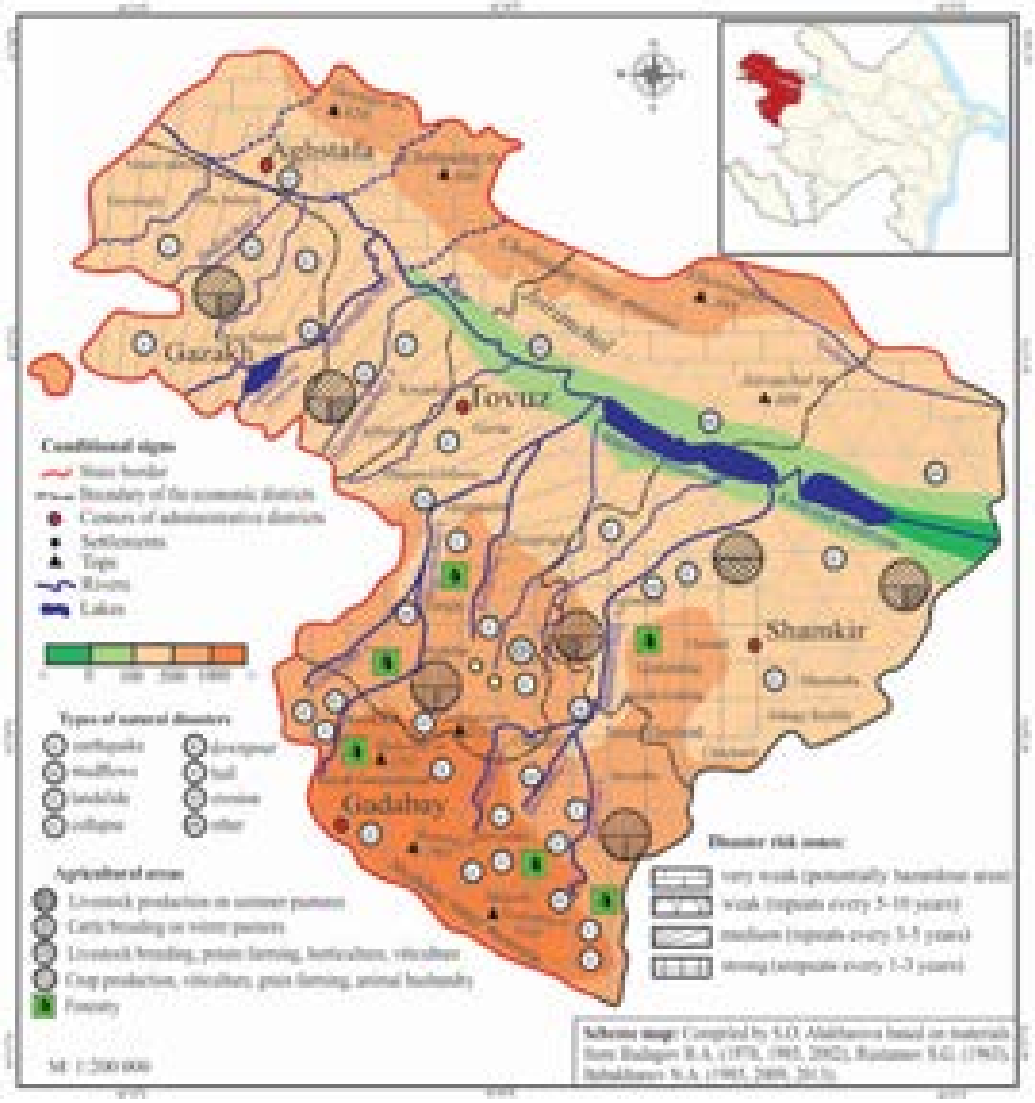


Fig. 3. Map of disaster risk assessment in the development of agricultural sectors
Source: The map developed, by S.O. Alakbarova, using data from the State Statistics Committee, the Ministry of Emergency Situations, State Programs, field research, and relevant publications

considers both environmental hazards and the capacity of agricultural systems to absorb and adapt to shocks (d):

$$TR = RI \times AI \qquad (d)$$

Where, *(TR)* is the total agricultural risk indicator, *(RI)* is the initial hazard index, *(AI)* is the agricultural impact index. This combined indicator allows for the identification of zones where high hazard potential coincides with intensive agricultural activity, thus prioritizing areas for risk mitigation strategies.

The risk index was calculated for each zone, and hazard maps, illustrating the most vulnerable areas with intensive agricultural activity, were compiled using modern information technologies (Fig. 3.).

Figure 3 depicts that the southern and western parts of the economic region are at risk, especially areas where agricultural lands are more developed. Disaster risk in the development of agricultural sectors of Gazakh-Tovuz economic region was assessed on 4 scales; 1. very weak (potentially hazardous area), 2. weak (repeats every 5-10 years), 3. medium (repeats every 3-5 years), 4. strong (repeats every 1-3 years).

The hazard index–based framework provides a scientifically rigorous, reproducible method for agricultural risk assessment. By integrating geospatial analysis, historical hazard data, and crop production characteristics, it supports the development of high-resolution risk maps. These maps are critical for evidence-based disaster preparedness, planning resilient and sustainable agricultural systems.

Building on this framework, the analysis of this map enables the evaluation of settlements and administrative territories in relation to hazard distribution and risk levels. In this context, the main demographic and geographical characteristics of the administrative districts of the Gazakh–Tovuz economic region, including

Table 2

Regional and risk characteristics of the Gazakh–Tovuz economic districts

District	Elevation of settlements (m)	Area, thausand km²	Population, thausand persons		Population density (persons/km²)		Risk level
			2019	2025	2019	2025	
Agstafa	215-600	1,50	84,7	86,7	56	58	very weak and medium
Gadabay	1100-2000	1,23	95,6	101,2	78	82	strong
Gazakh	215-820	0,70	94,3	96,5	135	138	medium
Shamkir	205-1500	1,66	211,6	218,3	127	132	weak and medium
Tovuz	340-2100	1,94	171,9	177,9	89	92	medium
By region	205-2100	7,03	658,1	680,6	94	97	moderate risk

Source: Calculated and compiled by the author using statistical data [16]

area, population size, population density, and the elevation range of settlements, are presented in Table 2. Based on the comparative analysis of these parameters, the risk levels for the administrative districts of the Gazakh–Tovuz economic region are assessed as follows (Table 2.).

The results indicate significant spatial differentiation among the administrative districts of the Gazakh–Tovuz economic region in terms of elevation, area, population, and population density. These variations play an important role in shaping regional development patterns and determining overall risk levels.

The continuous development of agricultural sectors is fundamental for ensuring both economic and social sustainability. Economic and geographical assessments enable the systematic evaluation of regional potentials, limitations, and spatial distributions (Fig. 4).

According to the State Programs on the Socio-Economic Development of the Regions of the Republic of Azerbaijan strengthening social insurance mechanisms plays a key role in mitigating the impacts of natural disasters on the agrarian sector [21]. The proposed model provides a scientifically grounded analysis of natural

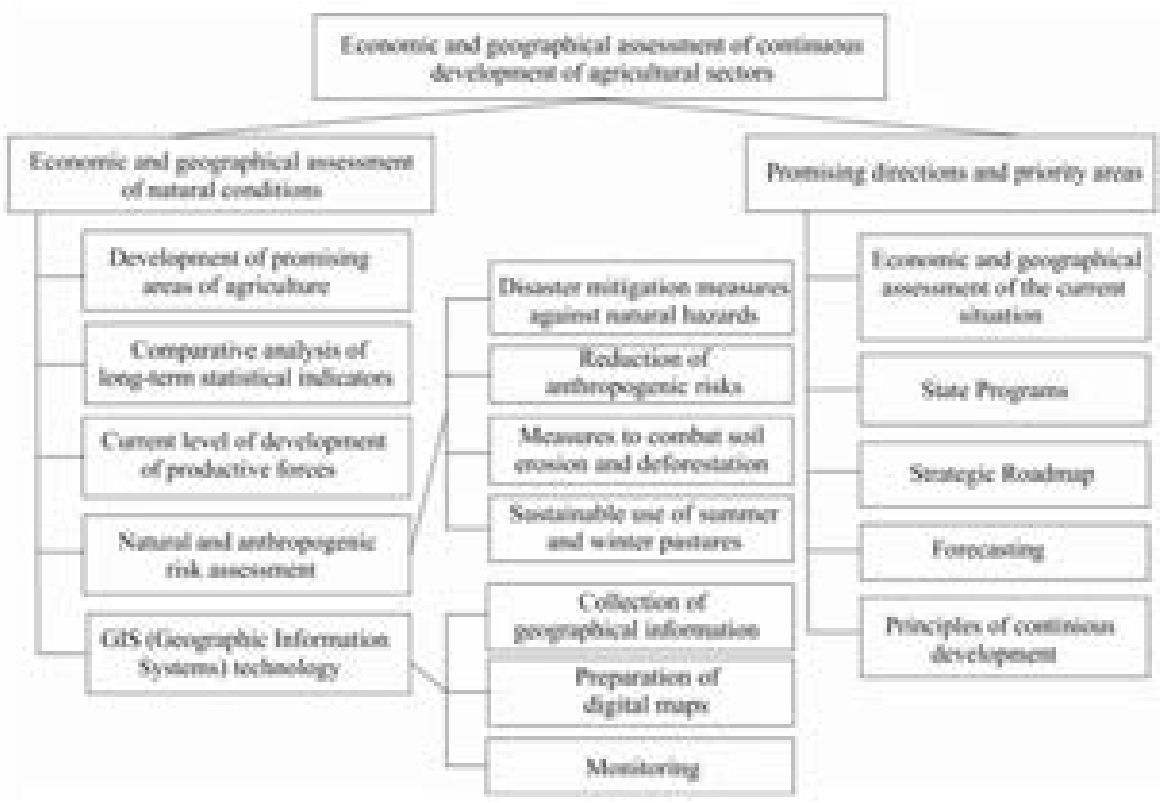


Fig. 4. Model for economic and geographical assessment of continuous development of agricultural sectors
Source: The model, developed by S.O. Alakbarova, is based on the analysis of opportunities, challenges, and measures for agriculture within the framework of State Programs aimed at sustainable territorial development [21]

risk factors for assessing the current level of agricultural development and identifying future prospects in the Gazakh–Tovuz economic region, thereby offering significant scientific and practical value for regional development planning.

Conclusion. Agriculture is one of the leading sectors in the Gazakh–Tovuz economic region; however, its development is strongly influenced by natural and anthropogenic risks, especially in areas with more intensive agricultural activity. The results demonstrate a clear spatial differentiation of risk across the region, where medium (20–33%) and strong (33–50%) risk zones cover a considerable part of the territory, exerting significant pressure on agricultural systems and rural settlement stability, while low-risk areas are comparatively limited. In medium and high-risk zones, recurrent natural hazards lead to substantial losses in crop production, livestock farming, and agricultural infrastructure.

In this context, increasing the effectiveness of risk management and monitoring systems is essential for ensuring sustainable agricultural development in the region. Currently, 70.1% of agricultural output is attributed to crop production and 29.9% to livestock farming, while state insurance compensates 30–40% of crop-related losses and 40–60% of livestock losses caused by natural and anthropogenic hazards.

Конфлікт інтересів: автор повідомляє про відсутність конфлікту інтересів.
Декларація про використання генеративного штучного інтелекту: автор підтверджує, що під час підготовки рукопису не використовувалися інструменти штучного інтелекту.

Conflict of Interest: The author declare no conflict of interest.
Declaration of use of generative artificial intelligence: The author confirm that no AI tools were used during the preparation of the manuscript.

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Вплив природних і техногенних ризиків на безпеку населення та розвиток сільського господарства в Газах–Товузькому економічному регіоні

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АНОТАЦІЯ

Це дослідження розглядає вплив природних і техногенних ризиків на безпеку населення та розвиток сільського господарства в Газах–Товузькому економічному регіоні. Особлива увага приділяється інтенсифікації природних катастроф в умовах зміни клімату. У роботі досліджується масштаб завданих такими явищами збитків сільським поселенням, орним землям, садам і присадибним ділянкам, а також їхній вплив на просторову організацію сільського господарства. Аналіз базується на статистичних даних, що дозволяє детально вивчити просторові та галузеві відмінності у вразливості регіону. Застосовано кількісну методологічну основу, де статистичні дані обробляються за допомогою математичних і аналітичних методів для забезпечення точності та надійності. Оцінювання ризиків здійснюється через інтегровану систему показників, що відображають інтенсивність, частоту, експозицію та вразливість. Ці показники систематично об'єднуються для отримання комплексної оцінки ризикових умов у регіоні. Крім того, для ранжування природних і техногенних ризиків застосовується метод аналізу ієрархій із використанням багатокритеріальної зваженої оцінки. Просторовий аналіз, підтриманий сучасними обчислювальними методами, використовується для виявлення та картографування зон підвищеного ризику в адміністративних районах, що забезпечує чітке відображення регіональних відмінностей. На основі просторового аналізу та сучасних комп'ютерних методів були розроблені карта ризиків для визначення територій із підвищеною вразливістю. Хоча поняття небезпечних явищ природного та антропогенного походження широко використовується як у науковій літературі, так і в практичній діяльності, досі не існує методу, який забезпечував би повне усунення або запобігання їхнім наслідкам. У цьому зв'язку вивчення та управління цими ризиками має особливе значення для сталого розвитку регіонів. Результати показують, що зміна клімату посилила частоту та вплив природних катастроф, значно підвищивши тиск як на сільськогосподарські системи, так і на системи розселення населення. Південні та західні частини Газах–Товузького економічного регіону визначені як найбільш вразливі території, де висока концентрація сільського господарства поєднується з підвищеним рівнем ризику. Дослідження підтверджує, що інтеграція оцінки ризиків із просторовим та статистичним аналізом є необхідною для вдосконалення регіонального планування та забезпечення сталого розвитку сільського господарства і систем розселення.

ІНФОРМАЦІЯ ПРО СТАТТЮ :

Рукопис надійшов
1 травня 2026

Отримано після рецензування
10 березня 2026

Затверджено до друку
25 травня 2026

Опубліковано онлайн
30 травня 2026

Ключові слова:

сільське господарство, оцінка ризиків, безпека населення, економіко-географічна оцінка, сталий розвиток, Газах-Товузький економічний регіон.

https://doi.org/10.26565/2410-7360-2026-64-10

УДК [911.5+913(477)]:502.6)

Ландшафтна сільськогосподарська спадщина м. Вилкове

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АНОТАЦІЯ

В Україні тема сільськогосподарської спадщини залишається недостатньо дослідженою попри відповідності подібних об'єктів концепції національної культурно-ландшафтної спадщини. Дослідження українських агроландшафтів, як культурної спадщини, є надзвичайно актуальним і сприяє науковому осмисленню унікальних форм традиційного землекористування, формуванню основи для їх охорони і інтеграції у стратегії сталого розвитку сільських територій. Метою даного дослідження є аналіз ландшафтної сільськогосподарської спадщини м. Вилкове задля визначення напрямів її збереження у контексті сталого розвитку регіону. Отже, пошук зразків українських агроландшафтів, як результату функціонування сталих систем ведення традиційного сільського господарства на окремих територіях, і визначило об'єктом дослідження сформовану поколіннями землеробів та рибалок Українського Подунав'я агровиробничу систему м. Вилкове (Вилківська МТГ, Ізмаїльський район, Одеська область). Предметом дослідження є: аналіз природної основи формування агроландшафтів території і визначення суспільних і культурних передумов формування агровиробничих систем; аналіз сучасного стану традиційної агровиробничої системи з визначенням перспективних напрямків охорони та збереження агроландшафтів. Методологічною основою обрано концепцію глобальної сільськогосподарської спадщини (GIAHS), включно з критеріями відбору територій до переліку цінних, положення типізації об'єктів охорони сільськогосподарської спадщини та системи захищених географічних зазначень (ГЗ), включно з формуванням переліку гарантованих традиційних особливостей України.
Основними результатами є те, що ландшафти м. Вилкове: розвиваються та характеризуються усталеним функціонуванням і відрізняються достатнім агробіорізноманіттям; є основою культивування цінних сільськогосподарських культур та видів (виноград сорту «Новак», «дунайка» тощо) і вирізняються унікальністю, адже функціонують в умовах сталого менеджменту місцевих фермерів (землеробів, скотарів, рибалок та ін.) задля підтримки засобів до існування, адаптивного управління та обміну знаннями.
У висновках зауважимо, що результати проведеного дослідження підтверджують унікальність агровиробничої системи м. Вилкове, як потенційного об'єкту охорони національної культурної спадщини, а агровиробнича система м. Вилкове може розглядатися як цінний об'єкт ландшафтної сільськогосподарської спадщини, що поєднує природні, культурні та соціально-економічні виміри.

ІНФОРМАЦІЯ ПРО СТАТТЮ :

Рукопис надійшов
22 січня 2026

Отримано після рецензування
20 травня 2026

Затверджено до друку
25 травня 2026

Опубліковано онлайн
30 травня 2026

Ключові слова:

агроландшафт, агровиробнича система, сільськогосподарська спадщина, культурна спадщина, GIAHS, географічні зазначення, м. Вилкове, дельта Дунаю.

Вступ

Наукові тлумачення українських вчених визначають агро- або сільськогосподарські ландшафти як антропогенні, функціонування яких спрямоване на забезпечення сільськогосподарської діяльності людей, тобто, території, основу яких становлять сільськогосподарські угіддя (поля, сіножаті, пасовища тощо) разом із штучними лісовими насадженнями [1, 2]. Натомість, у по-

Як цитувати : Аріон Оксана, Купач Тетяна, Олішевська Юлія, Дем'яненко Світлана (2026). Ландшафтна сільськогосподарська спадщина м. Вилкове. *Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology*, (64), 131–142. https://doi.org/10.26565/2410-7360-2026-64-10

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даних тлумаченнях не враховується ні естетична, ні історико-культурна складова таких утворень, а також, зауважимо, що частина земель сільськогосподарського призначення має значущість не лише з точки зору економічної, але і загальносуспільної цінності.

Враховуючи це, в даній роботі ми виходимо з тлумачення ландшафту викладеного в ст.1а Європейської ландшафтної конвенції [3] і розглядаємо сільськогосподарські ландшафти як культурні утворення, роблячи акцент на соціокультурній інтерпретації ландшафту, як такого, що включає нематеріальні компоненти, зокрема традицію землекористування та спільноту людей, які вплинули на розвиток даного ландшафту. Саме таке розуміння агроландшафтів покладено в основу концепції сільськогосподарської спадщини FAO, а також є підставою для включення ряду подібних територій до категорії культурних ландшафтів у World Heritage List (UNESCO).

Як показав джерелознавчий аналіз, проблематика сільськогосподарської спадщини досить широко представлена в закордонних публікаціях за останні 20 років. Разом із посиленням зацікавленості до проблем сільськогосподарської спадщини постають питання щодо: специфіки виокремлення унікальних сільськогосподарських систем з метою охорони в різних регіонах світу (Південна Азія, Європа та ін.) [4-6]; проблем моніторингу та оцінки об'єктів GIAHS [7-9]; застосування ГІС-методів для просторового аналізу факторів, які можуть впливати на цілісність ландшафту, зокрема, пов'язаних зі змінами у землекористуванні [10]; розгляду об'єктів GIAHS як невід'ємного елементу моделей сталого регіонального розвитку [6, 11, 12] та важливої складової продовольчої та харчової безпеки регіонів [13]; а також аналізу об'єктів сільськогосподарської спадщини з точки зору усвідомлення суб'єктивного благополуччя мешканців, сприйняття мешканцями впливу туризму та їх взаємодії з відвідувачами [14, 15].

Географія публікацій показує, що найбільша кількість досліджень пов'язана з об'єктами охорони сільськогосподарської спадщини країн Східної та Південної Азії, зокрема, Індія, Китай, Японія, Індонезія та ін., що пояснюється дисбалансом в просторовому розподілі сільськогосподарської спадщини: 14 об'єктів GIAHS в Європі проти 65 – в Азійсько-Тихоокеанському регіоні станом на 2025 рік [16]. Отже, дослідження агровиробничих систем є вельми актуальні з огляду на те, що такі системи є прикладом адаптації до умов навколишнього середовища (зокрема наслідків зміни клімату), а також сприяють збереженню біорізноманіття, захисту водозбірних басейнів, охороні ґрунтів та покращенню їх стану [17]. Окрім цього, виходячи з розуміння сільськогосподарських ландшафтів як частини спадщини кожного члена громади, унікальні системи землекористування та ландшафти (об'єкти GIAHS) розглядаються як моделі для формування більш сталого та процвітаючого майбутнього сільських та міських громад [18].

Разом з тим, за результатами аналізу джерел виявлено, що в Україні, попри наявність унікальних агровиробничих систем, тема сільськогосподарської спадщини залишається недостатньо дослідженою і у вітчизняних наукових публікаціях представлена поодинокими згадками [19]. Хоча подібні об'єкти цілком вкладаються в концепцію національної культурно-ландшафтної спадщини [20, 21] і, в особливих випадках, розглядаються як складова світової культурної спадщини [22].

З огляду на це, дослідження українських агроландшафтів, як культурної спадщини, є надзвичайно актуальним і новим. Воно сприятиме не лише науковому осмисленню унікальних форм традиційного землекористування, але й формуванню основи для їх охорони, популяризації та інтеграції у стратегії сталого розвитку сільських територій. Це дає підстави розглядати окремі агроландшафти, агровиробничі системи як потенційні об'єкти сільськогосподарської спадщини і складову національної культурної спадщини України в цілому.

Методологічною основою даного дослідження обрано концепцію глобальної сільськогосподарської спадщини GIAHS включно з критеріями відбору територій до переліку цінних [23], положення типізації об'єктів охорони сільськогосподарської спадщини за A. Nagata [24]. Виходячи з даних програми GIAHS, ландшафт не може існувати в структурі сільськогосподарської спадщини відірвано від місцевої традиції ведення сільського господарства. Тому, в подальшому, вважаємо за можливе використовувати поняття «агровиробнича система». В даному випадку, під агровиробничою системою ми розуміємо агроландшафт та відповідну йому систему традиційного господарювання, що сприяла його формуванню і тривалий період підтримує його стале функціонування.

Окрім цього, дослідження спирається на систему захищених географічних зазначень (ГЗ), включно з формуванням переліку гарантованих традиційних особливостей України [25, 26]. Пов'язані з ними унікальні агровиробничі системи розглядаються як потенційний об'єкт особливої охорони, що сприятиме збереженню агробіорізноманіття, сталому веденню господарства та соціо-економічному зростанню сільських громад [19].

Пошук зразків своєрідних українських агроландшафтів, як результату функціонування сталих систем ведення традиційного сільського господарства на окремих територіях, і визначило **об'єктом дослідження,** сформовану багатьма поколіннями землеробів та рибалок Українського Подунав'я, агровиробничу систему м. Вилкове.

Предметом дослідження є: аналіз природної основи формування агроландшафтів території і визначення суспільних і культурних передумов формування агровиробничих систем; аналіз сучасного стану традиційної агровиробничої системи з визначенням перспективних напрямків охорони та збереження агроландшафтів.

Метою дослідження є аналіз ландшафтної сільськогосподарської спадщини м. Вилкове (Вилківської міської територіальної громади) задля визначення стратегічних напрямів її збереження у контексті сталого розвитку регіону. Для досягнення поставленої мети виокремлені наступні **завдання**: здійснити аналіз природної основи формування агроландшафтів території м. Вилкове; визначити історичні та соціо-культурні передумови формування агровиробничих систем; проаналізувати їх сучасний стан та роль у житті місцевої громади, як складової традиційної агровиробничої системи; визначити перспективи охорони та збереження агроландшафтів, їх роль та культурну цінність для місцевої громади, регіону та України в цілому.

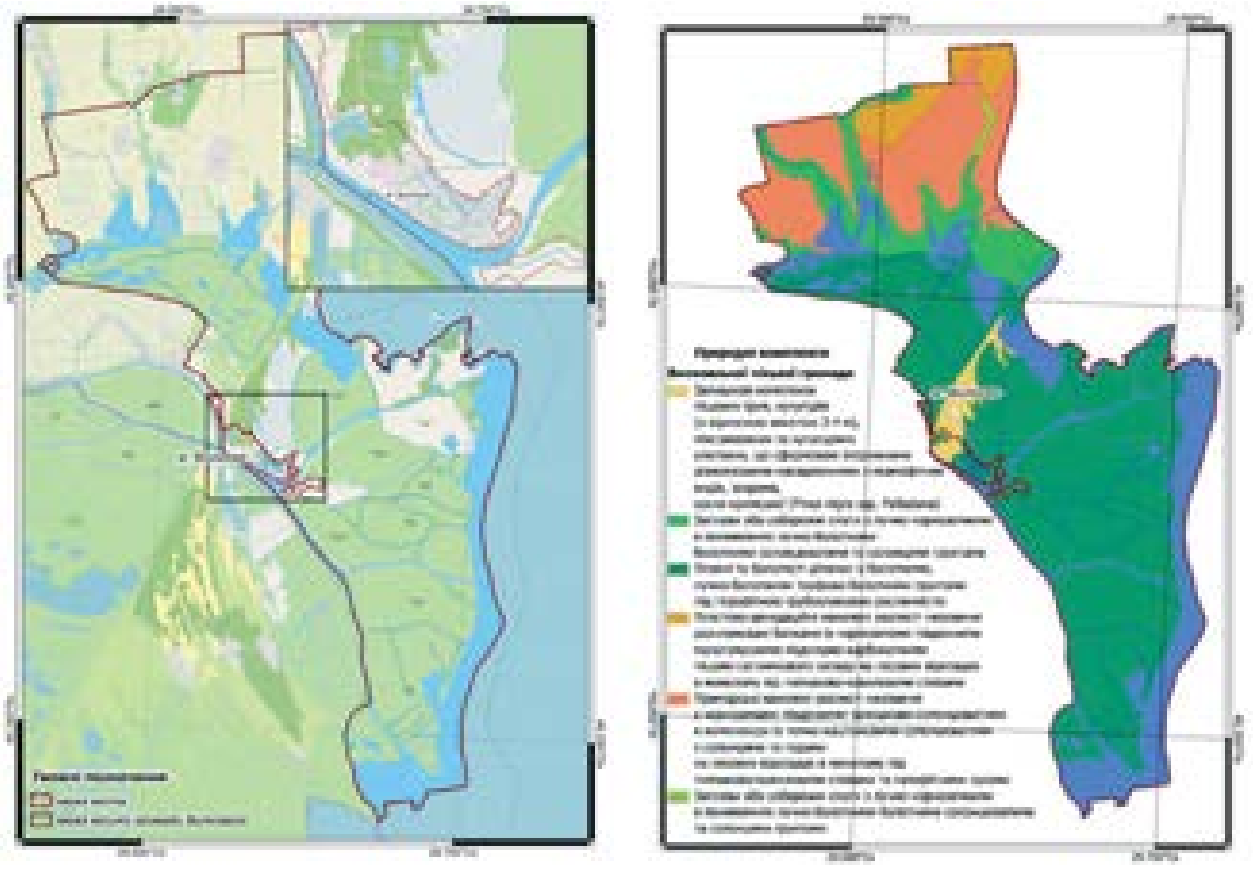
Результати та обговорення

Основними характеристиками об'єктів сільськогосподарської спадщини за визначенням FAO є такі, що вказують на те, що ландшафти: 1) розвиваються та характеризуються сталим функціонуванням; 2) відрізняються агробіорізноманіттям; 3) є основою культивування цінних сільськогосподарських культур (до прикладу, сортів зернових, овочів та фруктів, порід худоби та ін.); 4) вирізняються унікальністю, адже функціонують в умовах сталого менеджменту місцевих фермерів (землеробів, скотарів, рибалок та ін.) задля підтримки засобів до існування, адаптивного управління та обміну знаннями.

Зазначені характеристики ландшафтів конкретизуються у вигляді п'яти критеріїв запропонованих FAO [23], відповідно до яких здійснюється оцінка унікальності тих чи інших агровиробничих систем та приймається рішення щодо їх включення до переліку GIAHS. Кожен зазначений критерій представляє собою один з елементарних вимірів сільськогосподарської спадщини [23].

Вивчення ландшафтної сільськогосподарської спадщини проводилося для території м. Вилкове (Вилківська МТГ, Ізмаїльський район, Одеська область).

Регіон, в межі якого потрапляє територія дослідження, характеризується різноманітними природними умовами, що визначаються, перш за все, його географічним положенням (рис.1):



а б

Рис.1. а) Фізико-географічне положення території дослідження (дані: OSM); б) Природні комплекси території дослідження / **Fig. 1.** a) Geographical location of the research area (source: OSM); b) Natural complexes of the research area

розташуванням в межах української частини пониззя (дельти) р. Дунай. Регіон дослідження представляє собою власне дельту р. Дунай в її Кілійському гирлі. Власне м. Вилкове розташоване саме в місці, біля якого р. Дунай ділиться на Очаківський, Старостамбульський і Білгородський рукави. Нижче за течією вони утворюють ще більш дрібні протоки. Разом з численними великими і малими протоками існує мережа прісноводних внутрішніх і відкритих приморських мілководних водойм з глибинами від 0,5 до 2 м. Кілійська дельта вважається найбільш молодою частиною дельти р. Дунай (вік формування ~ 300 років) з формуванням окремих островів та кіс в дельті впродовж останніх десятків років. Процеси дельтоутворення, наразі, продовжуються, проте є менш інтенсивними в зв'язку з виносом мулу на більші глибини Чорного моря [27]. Для пониззя р. Дунай, в цілому, притаманний знижений рівнинний рельєф із незначними підвищеннями в північній частині. Найвищими природними формами є піщані дюни Жебріянівської гряди, приморські та прируслові гряди. Вартий уваги антропогенний рельєф, що формується як наслідок відвалів ґрунту від інтенсивних днопоглиблювальних робіт дельти.

Регіон, в межах якого знаходиться територія дослідження, потрапляє в зону з помірним напівпосушливим кліматом, типовим для південних помірно-сухих степів (Bsk або холодний степовий клімат за класифікацією Köppen-Geiger). В той же час, характерна для дельти р. Дунай та прилеглих лагун активна поверхня є значною мірою відмінною від поверхні степів, що призводить до формування мозаїки мікрокліматів, як реакції на загальну отриману радіацію та загальну циркуляцію атмосфери. Специфічні погодні умови встановлюються залежно від активності основних баричних центрів. Так, м'які зимові дні, що є характерними для території дослідження, залежать від активності північно-східноєвропейського баричного центру і часто змінюються морозними днями з сильними вітрами, які є наслідком дії північноатлантичних антициклонів. Дана специфіка переносу повітряних мас в межах регіону дозволяє віднести територію м. Вилкове до територій з вологим субтропічним типом клімату (Cfa, за класифікацією Köppen-Geiger).

Аналіз кліматичних даних за багаторічними середніми показниками [28] вказує на нерівномірний розподіл за порами року: літо (45 днів) значно довше за зиму (15 днів), весна (122 дні) триваліше за осінь (83 дні). Згідно зі статистичними даними середня температура в місті Вилкове становить 12,8 °С. За даними [28] для території дослідження характерним липневим показником найвищої температури з середнім значенням є 24,7 °С. Для січня зареєстровані найнижчі температури протягом року, з середнім мінімальним значенням в 0,4 °С. Річна амплітуда середньої температури складає 24,3 °С. Варто зауважити, що на території м. Вилкове впродовж року випадає достатньо велика кількість опадів, навіть у найменш вологий місяць (див. рис. 2).

Кількість опадів становить близько 474 мм на рік, з максимумом в червні - до 56 мм та мінімумом в лютому – до 29 мм. Також спостерігається значне коливання кількості опадів з амплітудою в 27 мм між місяцем з найменшою кількістю опадів (лютий) і місяцем з найбільшою кількістю опадів (червень). Сніговий покрив не значний і тримається не довго, лише в найсуворіші зими.

Річна тривалість сонячного сяяння для території м. Вилкове ~ 2950,09 сонячних годин із середньомісячним показником, що становить ~ 245,84 год. Липень, для м. Вилкове, є місяцем з найбільшою кількістю сонячних годин на день (середня тривалість у 12,8 годин) та із загальною кількістю у 395,6 сонячних годин. У січні спостерігається найменша кількість сонячних годин на день (середня тривалість у 3,8 годин) із загальною кількістю сонячних годин - 120,8

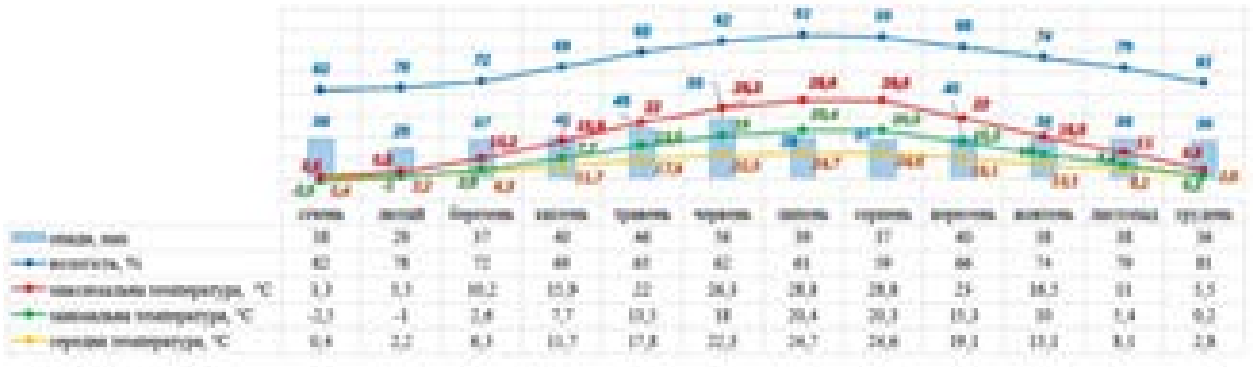


Рис. 2. Основні кліматичні дані за багаторічними середніми показниками для території м. Вилкове (дані Climate data за 1991 – 2021 роки)
Fig. 2. Basic climate data based on long-term averages for the territory of Vilkove (Climate data for 1991–2021)

(рис. 3). Відносна вологість повітря досить висока: коливається від понад 82% у січні до 59% у серпні місяці. Сума ефективних середньодобових температур в році наближається до 160°С.

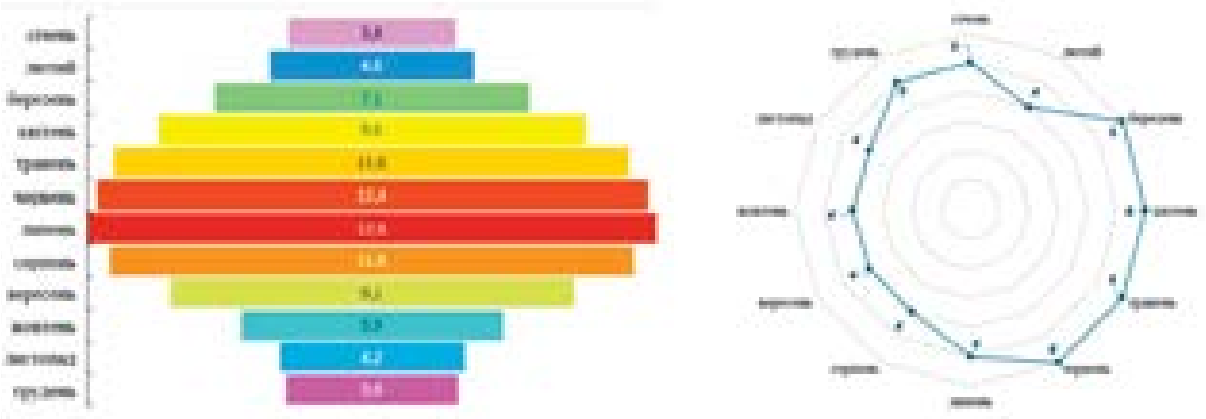
Випаровуваність значно перевищує кількість опадів і наближається до 800 мм/рік. Температура води в рукавах дельти р. Дунай сягає 12,7°С (в середньому за рік) з максимумом температури води в липні-серпні (27,6°С) та середнім її значенням у 24,1°С. Домінуючі вітри мають змінний північно-південний напрям з максимальними швидкостями вітру взимку та навесні та восени.

Ґрунти досліджуваної території сформувалися в результаті переважання дерново-лучного процесу за умови сильного та тривалого зволоження, здебільшого на субстратах мулистого та піщаного річкового алювію, піщаних літоральних відкладів. Для дельти найбільш характерними є важко суглинкові та глинисті відміни лучних, лучно-болотних, болотних ґрунтів (fluvisol за WRB- FAO, 2006) та їх засолених відмін. На знижених ділянках в дельтовій частині формуються найпоширеніші в регіоні болотні ґрунти. Присхилові ділянки прирусловых гряд займають лучно-болотні ґрунти які формуються в умовах постійного затоплення. Для центральної заплави р. Дунай характерними є дернові, лучно-чорноземні ґрунти, що сформувалися на алювіальних наносах різного механічного складу. Засолення ґрунтів (утворення солонців, солончаків) спостерігається на окремих ділянках із збіднілою або зведеною рослинністю, адже в періоди тривалих повеней, на решті ділянок, висока промивна здатність р. Дунаю захищає ґрунти від засолення.

Унікальність регіону, до якого належить територія м. Вилкове, щодо її насиченості біологічними видами відповідає дельтовим ландшафтам Кілійського гирла. Кілійська дельта є найбільш динамічною ділянкою дельти р. Дунай. Як вже зазначалося, ця територія сформована системою річкових рукавів, прісноводних та солоних озер і лиманів, а у структурі водного стоку складає до 63% від загального показника [29]. Все це впливає на формування значних за площами водно-болотних екосистем - плавнів. Плавні Кілійського гирла прорізані мережею рукавів, протоків та штучних каналів, чергуються із численними озерами та лиманами. Вони, за своїм визначенням, є підтопленими або заболоченими пригирловими ділянками в річкових долинах. Плавні вважаються перехідними ландшафтами, що представлені мозаїчними урочищами з домінуванням угруповань очерету (*Phragmites*), рогозу (*Scirpus*), осоки гострокінцевої (*Carex acuta*), серед яких зустрічаються чагарники та рідколісся з верби попелястої (*Salix myrtilloides*), вільхи чорної (*Alnus glutinosa*) тощо [30]. Для регіону, в межі якого потрапляє м. Вилкове, характерним є різноманіття і суходільних ландшафтів, зокрема, лісових заплавних, лучних, солончаків, морських теригенних (піщаних кіс та відмілин), степових тощо.

Лісові ландшафти представлені як природними угрупованнями, так і штучними насадженнями з різних видів *Pinus, Salix*, *Populus* тощо. Зокрема, ландшафт Жебріянівського піщаного пасма, що підступає до м. Вилкове з півночі, представлено рідкісними природними комплексами піщаних грив, кучугурів (з відносною висотою 3-4 м), міжгривенних та кучугурних улоговин, що сформовані вторинними різновіковими насадженнями з псамофітних видів, зокрема, сосни кримської (*Pinus nigra* ssp. *Pallasiana*).

Вздовж водотоків смугами від 5 до 200 м тягнуться зарості, утворені *Salix alba L., Salix*



а б

Рис. 3. Основні кліматичні дані за багаторічними середніми показниками для території м. Вилкове: години тривалості сонячного сяяння (а) та кількість днів з опадами (б) по місяцях з 1999 р. по 2019 р. (за даними Climate data)
Fig. 3. Key climate data based on long-term averages for the territory of Vilkove: hours of sunshine (a) and number of days with precipitation (b) by month from 1999 to 2019 (source: Climate data)

triandra L., Salix fragilis L., Populus nigra L., Populus tremula та ін., морське узбережжя засаджене: обліпихою (*Hippophae rhamnoides*), маслинкою (*Elaeagnus*), аморфою (*Amorpha fruticosa* L.), тамариксом (*Tamarix L.*), тополею білою (*Populus alba L.*) та ін. [30].

Лучні ландшафти, здебільшого, притаманні підвищеним ділянкам прируслових пасом, периферії плавнів, ділянкам дотичним до приморських піщано-моховаткових грив. Серед лучних ландшафтів виділяються: комплекси із крупнозлаковим, дрібнозлаковим трав'янистим покривом, крупнокомишовими та дрібноситниковими рослинними угрупованнями, а також різнотравною рослинністю засолених луків. Лучні ландшафти, які є трансформованими, за понад 100 років, процесами інтенсивного природокористування (перевипасу худоби, зокрема), характеризуються чергуванням з вологими луками з переважанням осоки струнко (*Carex chordorrhiza*), до якої додаються різноманітні галофітні види [30].

Великою різноманітністю відзначаються аквальні ландшафти: прісноводні, солонуваті, що розвиваються на водотоках, в лиманах, в озерах і «кутах». Біологічне різноманіття «кутів» є максимально урізноманітненим, адже, ландшафти повністю втратили зв'язок з морем. Аквальні ландшафти представлені рослинними угрупуваннями із домінуванням латаття білого (*Nymphaea alba*), глечиків жовтих (*Nuphar lutea*), водяного горіха (*Trapa natans* L.), плавуна щитолистого (*Nymphoides peltata*). Серед занурених рослин поширені кушир (*Ceratophyllum)*, різуха морська ((*Najas marina*), рдесники (*Potamogeton L.*), елодея (*Elodea*), тіліріз (*Stratiotes aloides*) тощо. Значні ділянки формуються з ряски (*Lemna* L.), сальвінії (*Salvinia*), жабурнику (*Hydrocharis*), азоли (*Azolla*) тощо [30].

Формуванням специфічних екосистем є контактна зона р. Дунай та Чорного моря. В гирло р. Дунай щорічно виноситься від 100 до 200 тис. тон прісноводного планктону, що гине і осідає на дно. Видовий склад і біомаса бентосу в Кілійському гирлі р. Дунай сприяє формуванню унікальних рис біологічного різноманіття: осетрові риби, дунайський оселедець тощо [31].

Більша частина території Вилківської громади, включно з околицями м. Вилкове, включена до Дунайського біосферного заповідника, що належить до Всесвітньої мережі біосферних резерватів (World Network of Biosphere Reserves, UNESCO) як складова частина транскордонного українсько-румунського біосферного резервату «Дельта Дунаю» [32]. Відповідно до біогеографічного районування та виділених екологічних регіонів Європи, територія дослідження відноситься до водно-болотних угідь Чорноморського біогеографічного регіону Європи [33] та Дністровсько-Нижньо-Дунайського прісноводного екорегіону (Dniester - Lower Danube: ID 418) з основним типом оселища: temperate floodplain rivers and wetlands [34]. Територія дослідження межує з еко регіоном Понтійських степових лук (Pontic Steppe: ID 735) [35].

Вилкове має давню історію освоєння: у Середньовіччі в районі сучасних Вилкове та румунського села Періправа (повіт Тулча, Добруджа), які розділяє рукав Кілія, розташовувався генуезький порт і фортеця, відомі як Лікостомо (грец. Λυκοστόμα - Вовча паща), який неодноразово змінював адміністративну приналежність [36]. У 1746 році на місці покинутого середньовічного міста групою старообрядців-липованів було засноване поселення, що до нашого часу має назву «Вилкове» (в румунських джерелах Vâlcov). Подальша історія міста пов'язана з наступними хвилями переселення донських козаків-некрасівців (1740 -1778 р.), а після 1775 р. також козаків із Запорозької Січі. Протягом XIX-XX ст. місто неодноразово змінювало політико-адміністративну приналежність, при цьому зберігаючи, вже сформовану на той час, систему господарювання, в якій ключову роль відігравало рибальство. Досить велика рибальська артіль зберігалася в містечку до 2-ої світової війни. Згадка про місто як «Маленьку Венецію» дельти р. Дунай і описи промислів видобутку осетрової ікри рибалками-липованами у 1939 р. для журналу National Geographic американською журналісткою Дороті Хосмер принесло світову славу місту Вилкове [37].

В структурі населення м. Вилкове нащадки православних старообрядців - липованів і до цього часу складають більшість населення міста ~ 70% згідно з переписом населення України 2001 року [38]. Власне липовани формують найбільшу релігійну конфесію міста, дотримуючись традиційного способу життя, частина з них проживають на островах Кілійської дельти, принципово відмовляючись від принад цивілізації, зокрема у використанні газу, електрики та ін. [39].

Як було зауважено вище, агровиробнича система м. Вилкове характеризується багатьма унікальними рисами, що свідчить про високий ступінь адаптації населення до природних умов дельти Дунаю. До початку XX ст. на території міста Вилкове була створена система каналів (місцева назва «єрики»), яка сполучала подовжньо-поперечною сіткою рукави Дунаю, що призвело до зниження рівня ґрунтових вод і вивільнення більшої частки землі для освоєння. Канали поєднують річкові рукави з городами, плавнями та міськими кварталами. Все це є прикметною особливістю міста і має

визначальний вплив на формування міського пейзажу.

Розвиток садівництва і городництва відбувається на багатих гумусом мулистих зволожених намивних ґрунтах островів, формування яких пов'язане з постійним підсипанням мулу, видобутого при регулярному розчищені каналів. Агробіорізноманіття забезпечується своєрідною триярусною системою садівництва: нижній займає полуниця, середній - виноград, у верхньому ярусі традиційно - груші, яблука, айва, а також нові для цієї місцевості види – хурма та гранати. Острови з садами і виноградниками кожні 10-15 м розділені каналами, вода з яких використовується для поливу, а мул - у якості добрива.

Вивезення продукції відбувається човнами, яких в місті нараховується понад 1,5 тисячі одиниць. Частково збереглися дерев'яні судна старого зразку – із загостреним носом та кормою, щоб рухатися каналами не розвертаючи човен. Завдяки м'якому клімату, сади приносять гарні врожаї. Полуниця дозріває в цій місцевості ранньою весною і постачання першої в Україні полуниці відбувається не лише по області, але й до столичного регіону. Місцевий сорт винограду «Новак» має унікальні смакові характеристики, пов'язані з агротехнікою його вирощування, і не зустрічається за межами громади. Виноград та вино «Новак» займають важливе місце у соціальній та культурній сферах життя липованів та інших мешканців міста і є невід'ємною частиною локальної кухні [40].

Як було згадано вище, ще в першій половині ХХ ст. основою міського господарства був вилов риби. Поступово традиційний риболовний промисел, пов'язаний з виловом осетра та сома скоротився, але залишається найголовнішим заняттям населення і невід'ємною складовою міського господарства. Станом на 2021 рік на території Вилківської громади функціонувало 14 риболовецьких кооперативів, чисельність яких в сезон налічувала від 700 до 900 рибалок. Головна промислова риба в м. Вилкове – азово-чорноморський прохідний оселедець (місцева назва «дунайка»). Як і вино «Новак», риба є невід'ємним елементом локальної гастрономії: «дунайку» традиційно солять, коптять на фруктових дровах; свіжу смажать на олії з борошном або варять [40, 41]. Ще одним місцевим спеціалітетом, пов'язаним з липованською кухнею, є «дунайська юшка», що готується з місцевої риби (судак, сом, сазан) та подається з гострим соусом під назвою «саламур», традиційним для рибалок Південної України [42].

Високий рівень адаптації місцевого населення до специфіки природних умов відбився і на історичній планувальній структурі міста, яка базується на системі островів і каналів: будинки стоять на острівцях, а вулиці – це канали, що для укріплення берегів обсаджені деревами, які потім вирубуються на дрова. Типова для степової зони, зокрема Української Бессарабії, каркасна/каркасно-плотова конструкція стін будинків, обмазана товстим шаром глини з кізяками і половою, у м. Вилкове замінена на каркасну з закладом снопами очерету, обмазаним мулом з січеним очеретом. На старих вулицях уздовж каналів простягаються нешироки, в кілька дошок, дерев'яні тротуари. Всього нараховується біля 70 островів, розділених каналами, загальна довжина яких складає біля 46 км. Це формує «стару» частину міста, населену переважно нащадками липованів. Для збереження автентичного ландшафту міста важливо підтримувати стан каналів, дерев'яних мостових переходів та кладок-тротуарів. Реновації відбуваються, як за рахунок бюджетних коштів, так і коштів благодійних фондів БФ [43].

Щодо громадських організацій Вилківської міської громади, які б сприяли підтримці традиційних видів господарювання, локальної гастрономії тощо, інформація у відкритих джерелах фактично відсутня. Натомість, м. Вилкове є осередком фестивалю гастрономічної спадщини «Дунайські гостини» (з 2018 р.) де представлені продукція місцевих фермерських господарств, локальні кулінарні спеціалітети та смаколики, а також різноманітні національні страви Української Бессарабії та продукція кращих регіональних виробників вин. У 2023 році за ініціативи ГО «Ініціатива «ЛЮДИ», у місті відбувся перший фестиваль української культури «ВиделкаFEST» (реалізовано в межах мистецького конкурсу Українського інституту книги, Культурних Сил та PEN Ukraine). Також відвідування міста та окремих його локацій включено до системи організованих еногастрономічних маршрутів «Дорога вина та смаку Української Бессарабії».

Для визначення потенціалу та ризиків збереження ландшафтної сільськогосподарської спадщини м. Вилкове були проаналізовані внутрішні та зовнішні чинники розвитку території. Серед ключових сильних сторін можемо виокремити довготривалу традицію унікальних землеробських практик, що забезпечила формування багатого агробіорізноманіття. Важливою перевагою є також унікальна просторова та планувальна структура міста Вилкове, яка поєднує природні та культурні особливості. До сильних сторін належить і обмежений ареал вирощування локального сорту винограду «Новак», що підсилює автентичність регіону. Значну роль відіграють традиції рибного промислу, зокрема вилову оселедця «дунайка» та осетрових риб, а також гастрономічна спадщина, сформована локальними продуктами. Ав-

тентичний побут і культурна спадщина липованів створюють додаткову культурну цінність. Регіон має значний туристичний потенціал, підсилений геобрендом «Українська Венеція».

Серед можливостей розвитку досліджуваного регіону варто виділити використання міжнародного досвіду охорони культурних агроландшафтів, зокрема підходів GIAHS та положень Європейської ландшафтної конвенції. Важливим ресурсом є міжнародні грантові програми та культурні проєкти, що можуть підтримати розвиток громади. Перспективним напрямом виступає розробка програми сталого туризму для м. Вилкове та всієї громади, включно з інтеграцією напрацювань «Доріг смаку та вина Бессарабії». Також додаткові можливості відкриває створення системи моніторингу стану агроландшафтів, оновлення геобренду регіону, розвиток освітніх і наукових партнерств, а також цифровізація спадщини через створення віртуальних турів.

Разом з тим, маємо і внутрішні слабкі сторони, до яких належить мала кількість об'єктів матеріальної культурної спадщини, а також застарілість і зношеність соціально-економічної інфраструктури. Доступ до островів із традиційними агровиробничими системами ускладнений через воєнний стан. Громада стикається з обмеженими фінансовими ресурсами та демографічними проблемами, зокрема відтоком молоді. Відчутною є нестача фахівців у сфері охорони спадщини, рекреації та туризму. Крім того, рівень інтеграції громади в проєкти охорони унікальних агроландшафтів залишається низьким.

Серед зовнішніх загроз ключовими є наслідки воєнного стану та військової агресії рф. Додаткові ризики створюють конфлікти між природоохоронними завданнями та потребами економічного й соціального розвитку громади. Обмеження щодо промислового вилову риби впливають на традиційні промисли. Зниження промивного режиму та маловодність каналів становлять загрозу для існування агроландшафтів окремих островів і можуть призвести до руйнації агровиробничої системи. Також зберігаються обмеження та контроль за доступом до окремих островів через прикордонне положення та воєнні ризики.

Проведений аналіз дозволяє окреслити стратегію та першочергові заходи спрямовані на охорону та збереження унікальних агроландшафтів м. Вилкове. Однією із ключових умов є завершення воєнних дій та впровадження інтегрованого підходу до управління, який поєднує охорону унікальних агроландшафтів та потреби місцевої громади. Ключовими напрямами подальших дій ми визначаємо наступні: провести комплексну інвентаризацію культурних ландшафтів м. Вилкове за співпраці експертів та місцевої громади; розробити заходи щодо інтеграції культурного ландшафту до Стратегії територіального розвитку міста; розробити план адаптації до кліматичних ризиків та загроз воєнного стану; використати унікальність території для просування бренду міста та розвитку сталого туризму; створити механізми довгострокового фінансування (партнерства, гранти, фонди).

Висновки. Отже, зважаючи на значний інтерес науковців і громадськості до охорони глобальної сільськогосподарської спадщини, зафіксований у відповідній програмі FAO – GIAHS, результати проведеного дослідження підтверджують унікальність агровиробничої системи м. Вилкове як потенційного об'єкту охорони національної культурної спадщини.

Природна основа формування агроландшафтів м. Вилкове визначається специфічними гідрологічними та геоморфологічними умовами Українського Подунав'я, що зумовили особливий характер землеробства у поєднанні з рибальськими практиками. Історичні та соціокультурні чинники забезпечили стійкість та неперервність функціонування агровиробничої системи, що формувалася протягом багатьох поколінь і стала невід'ємною складовою локальної ідентичності та свідченням високого рівня адаптації місцевої громади до природних умов.

Сучасний стан цілісного міського ландшафту м. Вилкове та агроландшафтів, зокрема, демонструє збереження традиційних форм господарювання, які продовжують відігравати важливу роль у соціально-економічному житті громади. Це має велике значення для ідентичності місцевої громади та адаптації її до викликів сталого розвитку та глобальних екологічних трансформацій.

Культурна та екологічна цінність агровиробничої системи м. Вилкове виходить за межі локального рівня: вона становить важливий елемент національної спадщини України та може бути інтегрована у міжнародні програми охорони сільськогосподарської спадщини.

Перспективи збереження та розвитку полягають у розробці комплексних стратегій охорони, інтеграції місцевих агроландшафтів у практики культурного, еногастрономічного та екотуризму, освітні та наукові програми, що сприятиме підвищенню добробуту місцевої громади та формуванню позитивного іміджу регіону на міжнародному рівні.

Таким чином, агровиробнича система м. Вилкове може розглядатися як цінний об'єкт ландшафтної сільськогосподарської спадщини, що поєднує природні, культурні та соціально-економічні виміри. Її збереження та інтеграція у сучасні стратегії сталого розвитку є важливим завданням як для локальної громади, так і для державної політики у сфері охорони культурної та природної спадщини.

Внесок авторів: всі автори зробили рівний внесок у цю роботу
Конфлікт інтересів: автори повідомляють про відсутність конфлікту інтересів
Декларація про використання генеративного штучного інтелекту: автори підтверджують, що під час підготовки рукопису не використовувалися інструменти штучного інтелекту..

Authors Contribution: All authors have contributed equally to this work
Conflict of Interest: The authors declare no conflict of interest

Declaration of use of generative artificial intelligence: The authors confirm that no AI tools were used during the preparation of the manuscript.

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Landscape agricultural heritage of the Vylkove town

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ABSTRACT

In Ukraine, the topic of agricultural heritage remains insufficiently researched despite the fact that such objects correspond to the concept of national cultural and landscape heritage. Research into Ukrainian agricultural landscapes as cultural heritage is extremely relevant and contributes to the scientific understanding of unique forms of traditional land use, the formation of a basis for their protection, and their integration into strategies for the sustainable development of rural areas. **The purpose** of this study is to analyze the agricultural landscape heritage of the Vylkove region in order to determine strategic directions for its preservation in the context of sustainable regional development. Thus, the search for examples of Ukrainian agricultural landscapes, as a result of the functioning of sustainable traditional farming systems in certain areas, determined the object of the study: the agricultural production system of the town of Vylkove, formed by generations of farmers and fishermen of the Ukrainian Danube region (Vylkivska local community, Izmail district, Odesa region). **The research focuses** on analyzing the natural basis for the formation of agricultural landscapes in the region and identifying the social and cultural prerequisites for the formation of agricultural production systems; analyzing the current condition of the traditional agricultural production system and identifying promising directions for the protection and preservation of agricultural landscapes.
The methodological basis is the concept of Globally Important Agricultural Heritage Systems (GIAHS), including criteria for selecting territories for inclusion in the list of valuable sites, provisions for the classification of agricultural heritage sites, and the system of protected geographical indications (GI) including the formation of a list of guaranteed traditional characteristics of Ukraine.
The main results are that the landscapes of the town of Vylkove: are developing and characterized by stable functioning and sufficient agrobiodiversity; are the basis for the cultivation of valuable agricultural crops and species (grapes «Novak» and «Dunayka», etc.) and are distinguished by their uniqueness, as they operate under the sustainable

ARTICLE INFO

Manuscript received
22 January 2026

Revised manuscript received
20 May 2026

Manuscript accepted
25 May 2026

Available online
30 May 2026

management of local farmers (arable farmers, livestock farmers, fishermen, etc.) to support livelihoods, adaptive management, and knowledge sharing.

Therefore, in ***conclusion***, we note that the results of the study confirm the uniqueness of the agricultural production system of the town of Vylkove as a potential object of national cultural heritage protection, and the agricultural production system of the city of Vylkove can be considered a valuable object of landscape agricultural heritage, combining natural, cultural, and socio-economic dimensions. Its preservation and integration into modern sustainable development strategies is an important task for both the local community and state policy in the field of cultural and natural heritage protection.

Keywords:

agricultural landscape, agricultural production system, agricultural heritage, cultural heritage, GIAHS, geographical indications, Vylkove, the Danube Delta.

In cites: Oksana Arion,Tetiana Kupach, Yuliia Olishevska, Svitlana Demianenko (2026). Landscape agricultural heritage of the Vylkove town. *Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology*, (64), 131–142. https://doi.org/10.26565/2410-7360-2026-64-10 [In Ukrainian]

https://doi.org/10.26565/2410-7360-2026-64-11

UDC 911.375:332.142:502.131(100)

Creating an international brownfields collaborative

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ABSTRACT

Introduction. Brownfields and blighted sites are present in all countries and represent significant environmental, public health, economic, and spatial planning challenges. Military, war, and post-war brownfields are becoming increasingly important in the context of contemporary armed conflicts and post-war recovery, particularly in Ukraine. In response to these challenges, experts from the United States, Canada, Romania, and Ukraine established the United States – Eastern European Brownfields Working Group in 2015 to promote community-engaged land reuse and public health-oriented redevelopment approaches. The purpose of this study is to analyze the formation and development of the International Brownfields Collaborative as an interdisciplinary platform for addressing military, war, and post-war brownfields through international cooperation, sustainable redevelopment, environmental security, and public health-oriented approaches.
Methods. The study applies a qualitative collaborative case-study approach based on workshop activities, expert discussions, educational initiatives, and interdisciplinary knowledge exchange conducted within the framework of the NATO Advanced Research Workshop (ARW) Achieving Sustainability in Ukraine through Military Brownfields

ARTICLE INFO

Manuscript received
20 April 2026

Revised manuscript received
22 May 2026

Manuscript accepted
25 May 2026

Available online
30 May 2026

In cites: Berman Laurel, DeSousa Christopher, Erdal Serap, Kovács Zoltán, Morar Cezar, Niemets Liudmyla, Shareef Huda (2026). Structural Framework and Petroleum Systems of the Kurdistan Creating an international brownfields collaboratives. *Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology*, (64), 143–152. https://doi.org/10.26565/2410-7360-2026-64-11



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Redevelopment. The research examines the evolution of the initial working group into the International Brownfields Collaborative and analyzes its scientific, educational, and organizational activities related to sustainable land reuse and post-war recovery.
Results. The ARW became a platform for expanding the initial working group of five experts from four countries into the International Brownfields Collaborative, which currently includes more than 20 members from 15 countries. The Collaborative united researchers, planners, environmental and public health professionals, educators, and practitioners working in brownfields redevelopment, environmental security, sustainable development, urban resilience, and spatial planning. The study highlights the growing significance of war and post-war brownfields as distinct categories of degraded territories formed by military activity, infrastructure destruction, environmental contamination, and socio-spatial transformation. The Collaborative contributed to disseminating interdisciplinary approaches to brownfields revitalization through workshops, publications, educational initiatives, and Environmental Health and Land Reuse (EHLR) training activities implemented at V. N. Karazin Kharkiv National University. These activities strengthened international academic cooperation, knowledge exchange, and sustainability-oriented competencies among graduate students and young researchers.
Discussion and Conclusions. The experience of the International Brownfields Collaborative demonstrates the importance of interdisciplinary international networks in addressing environmental, socio-spatial, and public health challenges associated with military, war, and post-war brownfields. The study emphasizes the need to integrate sustainable development principles, environmental security, public health, and resilience-oriented spatial planning into post-war recovery strategies. The findings may support policymakers, planning institutions, and academic communities in developing integrated approaches to sustainable redevelopment and environmental recovery in conflict-affected territories.

Keywords:

brownfields; military brownfields; war brownfields; post-war brownfields; contamination, sustainable redevelopment; environmental security; public health; urban resilience; international collaboration.

Introduction

Brownfields and blighted sites are present in all countries, posing public health, environmental, and economic impacts. In 2012, a group of colleagues with expertise in land reuse and community revitalization launched the Brownfields & Opportunity Working Network (BROWN). At the time, a federal public health agency facilitated BROWN. Since that time, BROWN has evolved into its own independent network, hosted by a nonprofit in the United States. The original goal of BROWN was to assist communities with brownfields. BROWN partners include planners, public health professionals, academics, engineers, and many others. As BROWN developed, we began to look at differences between brownfields regulation and policies in the United States, Canada, and Eastern Europe. We created the United States – Eastern European Brownfields Working Group as a vehicle for exploring and comparing brownfields redevelopment globally.

As a working group, we explored ways to create shared resources and best practices, including funding for research and site visits. We have a common interest in community-engaged land reuse that can improve community health. This health-focused approach to redevelopment broadens the typical economic drivers of redevelopment. For example, drawing on the expertise of community members who know their community's needs and visions may lead to a more robust and successful redevelopment project. In addition, by engaging a wide array of community members and partners from multiple sectors, such as education, environmental regulation and science, and health agencies, a sustainable redevelopment plan can develop and flourish.

One common thread is that brownfields are present in all countries. We are most interested in military brownfields, as they pose various challenges and offer large-scale opportunities for health-focused, sustainable redevelopment models. Through our Unites States – Eastern European Brownfields Working Group, we explored and researched brownfields definitions, contaminants of concern, regulatory and policy guidance, and funding for redevelopment of both brownfields and military brownfields. We envisioned growing our small working group in our four home countries – United States, Canada, Romania, and Ukraine – into a broader, International Brownfields Collaborative.

To reach our goal, we participated in several activities. We visited brownfields in Romania and the United States. We also published a 3-part series about brownfields redevelopment in Europe and the United States. In this series, we explored sustainable brownfields redevelopment through regulatory, policy, funding, and visual lenses [3, 4, 12]. In 2023, we were awarded NATO funding to host an Advanced Research Workshop (ARW), Achieving Sustainability in Ukraine through Military Brownfields Redevelopment. The ARW provided the opportunity to expand and launch our International Brownfields Collaborative.

Brownfields: Contaminants of Concern. The United States Environmental Protection Agency defines brownfield sites as "properties that contain or may contain a hazardous substance, pollutant or contaminant, complicating efforts to expand, redevelop or reuse them" [19]. In Europe, the concept of "brownfields" does not have a common

or legal definition. The term brownfields refers to "contaminated land" in general [6, 8].

The Agency for Toxic Substances and Disease Registry's (ATSDR's) review of United States Environmental Protection Agency brownfields data indicated common contaminant categories of brownfields. From the most to least frequent, these are: Lead, chromium, cadmium, mercury, arsenic, volatile organic compounds (VOCs), petroleum, polycyclic aromatic hydrocarbons (PAHs), and asbestos [5, 20]. These contaminants are found globally in blighted or former industrial sites. Many of these contaminants are found in all types of brownfields, including military brownfields.

Military Brownfields. Globally, there are thousands of military brownfield sites that include bases, munitions or arsenal sites, small sites such as lighthouses, and sites with complex pollution profiles. In Europe, military brownfields include war-damaged properties. The Eastern Bloc and historic wartime activities throughout Europe created military brownfields and war-scarred lands, contributing to the European brownfields burden. Military brownfields may contain typical contaminants found at brownfields in general, such as lead-based paint and petroleum compounds. Military brownfields also may contain the following [23]:

- Military vehicles (tanks)
- Unsafe buildings, structures, or debris
- Hazardous, toxic, and radioactive waste, which may include arsenic, certain paints, some solvents, petroleum and related products
- Toxic pollutants from landfills
- Radioactive waste, including wastes in underground and aboveground storage tanks.

In the United States, the Base Realignment and Closure (BRAC) Process determines and identifies if sites are military brownfields [21]. There are 136 BRAC sites and 9,300 Formerly Used Defense Sites (FUDS) in the United States and its territories [21, 24]. As of September 2021, 5,400 FUDS sites required investigation and cleanup. Of this total, 3,800 were cleaned up. There are 1,600 additional FUDS that required a cleanup response [24].

Military brownfields contamination is often more extensive than contamination at other types of brownfields. For example, in the United States, BRAC site contamination may be severe enough to list the site on the National Priorities List (NPL). The NPL is the list of sites of national priority among the known or threatened releases of hazardous substances, pollutants, or contaminants throughout the United States and its territories. The NPL is intended primarily to guide the EPA in determining which sites warrant further investigation. In 2024, 34 BRAC sites were listed on the NPL [22]. The majority of brownfields are not listed on the NPL or comparable state lists [7].

The complex chemical signature found globally in military brownfields may pose real and potential danger and hazards to nearby populations and the natural environment. Contaminants from military brownfields degrade the environment, public health, and the economy. For example, civilian and military fire fighters in the United States used fire-fighting foam for many years. This led to water contamination with per- and polyfluoroalkyl substances (PFAS) [18]. Exposure to contamination at military brownfield sites by inhalation, ingestion, or dermal contact exposure routes may cause adverse impacts on population health. Associated health issues may include respiratory and systemic illness, cancer, and skin irritation. Site contaminants may be present in:

- Surface and subsurface soil
- Groundwater aquifers
- Outdoor air
- The indoor environment of buildings or adjacent facilities
- Surface water bodies
- Sediments
- Biota, such as fish and game

Developers may view redevelopment of former military brownfields for beneficial re-use as risky investments. This may delay or prevent redevelopment, which can increase the exposure duration and health risks for the populations affected. Furthermore, contamination may be unknown due to lack of knowledge about site history. Site investigation efforts are expensive and create uncertainty in terms of economic investment and economic productivity.

The former Soviet Union and Ukraine contained more than 3,000 military bases of different sizes. After the fall of the Soviet Union in the early 1990s, military reform reduced the number of military units and weapons in the Ukrainian Armed Forces. This contributed to an economic decline in the regions of the former military facilities, leading to various social and environmental problems [9]. Recent crises in Ukraine may have contributed to the development of new brownfields as well as potentially added to contamination at existing brownfield sites. Reconstruction planning may consider the pre-existing vulnerable status of Ukraine and how this vulnerability developed. An important lesson is to avoid further brownfields and environmental harm in the global reconstruction efforts of Ukraine.

In the context of contemporary armed conflicts, particularly the Russian invasion of Ukraine, the concept of brownfields has expanded beyond traditional post-industrial and military

sites. Researchers increasingly emphasize the emergence of war brownfields and post-war brownfields as a distinct category of degraded territories formed directly or indirectly through military actions, destruction of infrastructure, environmental contamination, and forced transformation of urban and rural landscapes [11]. War brownfields include territories damaged during active hostilities, such as destroyed industrial enterprises, military facilities, residential districts, transport infrastructure, energy systems, and contaminated urban spaces [15]. The emerging concept of war and post-war brownfields extends traditional brownfields discourse by incorporating conflict-related environmental degradation, urban destruction, and post-war spatial transformation into sustainable redevelopment frameworks. Unlike conventional brownfields, these territories are characterized not only by physical degradation and economic decline, but also by complex environmental risks associated with explosive remnants of war, damaged industrial facilities, fuel spills, heavy metals, construction debris, and potential chemical contamination. In many cases, war brownfields emerge rapidly and simultaneously across large territories, creating unprecedented challenges for environmental security, spatial planning, and public health. Post-war brownfields represent the longer-term legacy of armed conflict and military destruction. They reflect territories requiring remediation, environmental assessment, functional transformation, and reintegration into regional development systems. As noted in studies focused on Ukraine, military aggression has intensified the formation of new brownfields while simultaneously transforming existing industrial and military brownfields into more complex and hazardous socio-environmental systems [15]. The scale of destruction in Ukrainian cities demonstrates that post-war reconstruction cannot be limited to physical rebuilding alone but must incorporate principles of sustainable development, environmental restoration, resilience, and community-oriented planning.

Recent research on Ukraine emphasizes that war and post-war brownfields should be considered not only as degraded spaces but also as territories of potential transformation and sustainable redevelopment. Their regeneration creates opportunities for implementing green infrastructure, nature-based solutions, renewable energy systems, sustainable mobility, and innovative urban planning approaches. In this regard, brownfields redevelopment becomes closely connected with broader processes of urban resilience, ecological recovery, and post-war regional transformation [13, 15].

Despite growing international attention to brownfields redevelopment, limited research has examined the role of transnational interdisciplinary collaborations in addressing military, war, and post-war brownfields through integrated public health, environmental security, and sustainable development approaches. The International Brownfields Collaborative represents an emerging platform that combines expertise from geography, urban studies, environmental sciences, public health, and spatial planning to support knowledge exchange, capacity building, and sustainable redevelopment strategies in both NATO and NATO-partner countries.

The purpose of this study is to analyze the formation and development of the International Brownfields Collaborative as an interdisciplinary platform for addressing military, war, and post-war brownfields through sustainable redevelopment, environmental security, and public health-oriented approaches. The object of the study is international cooperation in the field of brownfields redevelopment and sustainable land reuse. The subject of the study includes interdisciplinary collaborative practices, educational initiatives, and knowledge exchange mechanisms related to military and post-war brownfields redevelopment within the framework of the International Brownfields Collaborative.

Methods. We used the ARW as a springboard to build our small United States – Eastern European Brownfields Working Group of five people from four countries – United States, Canada, Romania, and Ukraine – into an International Brownfields Collaborative. The study applies a qualitative collaborative case-study approach based on international workshop activities, expert discussions, educational initiatives, and interdisciplinary knowledge exchange conducted within the framework of the NATO Advanced Research Workshop. During the ARW, we focused on Ukraine as a NATO-partner country to assist efforts to preserve and sustainably rebuild the country's assets and military brownfields. The ARW participants have expertise in urban planning, brownfields redevelopment (i.e., geography and tourism), and environmental public health.

The ARW presentations and brainstorming sessions occurred over four days organized into three panels. The brownfields topics included decision making, socio-economic aspects, and sustainable development, as described below.

Panel 1: Scientific Support for Decision Making in the Environmental Security Sector. Presentations in this panel emphasized international cooperation on assessing, surveying, and developing mitigation plans to prevent environmental hazards from defense-related

activities and installations. Each country relies on environmental regulations, policies, and multiple funding strategies to redevelop brownfields. By incorporating a public health focus, we emphasized the need to engage communities in brownfields redevelopment. Such engagement occurs by collaborating with regulatory and planning sectors, using community engagement techniques, and measuring environmental and health change. During Panel 1, we included a 2-hour Environmental Health and Land Reuse Training module: Evaluating Environmental and Health Risks [1]. The training provided an overview of environmental health topics, including toxicology and risk assessment. The training also described Phase I and Phase II environmental site assessments used in the United States, as well as ATSDR's public health assessment process [2].

Panel 2: Socio-Environmental Aspects of Reusing Former Military Lands. This panel focused on collaboration on the social and environmental aspects of reusing former military lands. The panel featured the most practical and cost-effective remediation techniques while raising public awareness about the benefits of brownfields reuse. Presentations in this panel focused on engaging communities and assessing environmental characteristics of military lands, including types of contamination and risk assessment approaches.

Panel 3: Global Approach to Brownfields Reuse – Sustainable Communities: A Special Focus on NATO-Partner Countries. Presentations in this panel described various aspects of brownfields redevelopment, including the similarities and differences in regulations, practices, and policies among NATO and NATO-partner countries. Several presentations examined varying aspects of sustainable redevelopment and military brownfields redevelopment as models for NATO-partner countries. For example, one presentation focused on reusing military brownfields as areas for recreation and landscape protection in the Czech Republic. Other presentations highlighted successful transformation of military brownfields in different regions of Ukraine.

Results and Discussion. Academics, graduate students, and municipal agency representatives attended the ARW. Through the workshop, our United States – Eastern European Brownfields Working Group developed into the International Brownfields Collaborative. The early goals of the International Brownfields Collaborative included

1) Developing and disseminating novel approaches and community-based solutions for brownfields site characterization, restoration, and revitalization.

2) Disseminating best practices for brownfields assessment and reuse to the scientific and regulatory community; policymakers; environmental groups; and local communities. This activity will raise awareness about brownfields.

The collaborative has over 20 partners from 15 countries. These include Albania, Bosnia and Herzegovina, Canada, Czech Republic, Germany, Hungary, Italy, Macedonia, Poland, Romania, Serbia, Spain, Turkey, Ukraine, and the United States. The International Brownfields Collaborative includes environmental public health practitioners; professors and students in public health, city planning; and geography and tourism.

The ARW showcased presentations on a wide array of brownfields redevelopment. The ARW presentations and brainstorming sessions raised awareness about brownfields in general and led to new collaborations among participants and our newly formed International Brownfields Collaborative. One area of interest was the increasing number of brownfields in Ukraine. Participants acknowledged Ukraine's vulnerabilities for future reconstruction efforts.

Since the December 2023 workshop, members of the International Brownfields Collaborative worked jointly on several projects. They formed new and strengthened existing international partnerships. They also built knowledge and capacity through environmental health training. Additionally, members shared best practices through collaboration and education. Some highlights of the International Brownfields Collaborative are described below.

Publications: Workshop participants submitted 35 manuscripts based on their ARW presentations and research for publication in a Springer book, supported by the NATO Science for Peace and Security Program. These included co-authored manuscripts developed through new collaborations of our International Brownfields Collaborative and a special section featuring the work of doctoral students and young researchers. Springer published the manuscripts in 2024 in the book, Achieving Sustainability in Ukraine through Military Brownfields Redevelopment [11].

2025 Workshop: In 2025, V. N. Karazin Kharkiv National University hosted the international scientific and practical seminar Interdisciplinary Research of Urbanized Spaces in the Context of Sustainable Development and the workshop Urban Kharkiv: Planning a Sustainable Urban Future. These events brought together researchers, graduate students, practitioners, representatives of public authorities, business, and civil society organizations from Ukraine and several European countries. The discussions focused on interdisciplinary approaches to sustainable urban development in the context

of contemporary environmental and socio-political challenges. Particular attention was paid to post-war urban recovery in Ukraine, urban resilience, renaturalization, green transition strategies, GIS and remote sensing applications in urban studies, sustainable mobility, cultural heritage preservation, and European integration perspectives for Ukrainian cities and regions. The workshop also served as a platform for strengthening cooperation among members of the International Brownfields Collaborative and expanding dialogue between academia, local authorities, and community stakeholders. In addition, students and young researchers presented innovative concepts and practical solutions related to energy efficiency, renewable energy, smart city technologies, urban memorialization, and sustainable waste management within a special EXPO exhibition [10, 25].

Environmental Health and Land Reuse (EHLR) Training: Another important outcome of the International Brownfields Collaborative was the implementation of the Environmental Health and Land Reuse (EHLR) Training initiative at V. N. Karazin Kharkiv National University in 2025 [17]. The training, developed under the leadership of Laurel Berman and colleagues from the Agency for Toxic Substances and Disease Registry (ATSDR), was delivered virtually as a specialized mini-course for 46 faculty members and doctoral students. The initiative reflected the Collaborative's broader objective of strengthening international cooperation in the fields of environmental security, sustainable redevelopment, and public health-oriented approaches to brownfields revitalization.

The EHLR training integrated interdisciplinary approaches to brownfields redevelopment, environmental health assessment, public participation, sustainability, and community resilience. The mini-course combined theoretical foundations with practical case studies and international experience related to land reuse and contaminated site redevelopment. Particular attention was devoted to the integration of environmental and health considerations into planning and redevelopment processes, especially in territories affected by industrial decline, military activity, and war-related destruction.

The training program incorporated five thematic modules: Engaging with Your Community, Evaluating Environmental and Health Risks, Communicating Environmental and Health Risks, Redesign with Health in Mind, and Measuring Success: Evaluating Environmental and Health Change. These modules addressed methods of community engagement in redevelopment planning, approaches to environmental and health risk assessment, communication strategies for vulnerable populations, principles of health-oriented redevelopment, and systems for monitoring environmental and public health changes during long-term revitalization processes.

The implementation of the EHLR initiative contributed to strengthening institutional and educational capacity at V. N. Karazin Kharkiv National University and expanded opportunities for integrating international expertise into educational and research activities. The initiative also facilitated the dissemination of public health-oriented redevelopment approaches among young researchers and academic staff working in geography, urban studies, environmental sciences, and spatial planning. The International Brownfields Collaborative envisages further development of joint educational activities, specialized courses, and guest lectures involving international experts in sustainable redevelopment and environmental security [17]. The Collaborative also highlights the increasing role of international academic cooperation in advancing education for sustainable development under conditions of environmental, social, and geopolitical instability. Recent studies in geographical and environmental education emphasize that sustainable development-oriented learning should integrate interdisciplinary approaches, spatial thinking, environmental awareness, and community engagement in order to address contemporary global and regional challenges effectively. In this context, geographical education plays an important role in supporting resilience-oriented approaches to environmental management, post-war recovery, and spatial planning [14]. The integration of interdisciplinary educational initiatives, training programs, workshops, and collaborative research activities within the International Brownfields Collaborative contributes to the development of sustainability-oriented competencies, supports knowledge exchange between institutions and countries, and strengthens the capacity of universities to address contemporary challenges related to environmental security, urban resilience, and post-war reconstruction [16].

In the future, members of the International Brownfields Collaborative plan to expand joint educational initiatives through additional trainings, guest lectures, and collaborative academic activities involving international partners.

BROWN Expansion: The United States – Eastern European Brownfields Working Group has grown into the International Brownfields Collaborative, which also expands BROWN's reach and membership. In 2025, BROWN became independently hosted by a nonprofit organization.

This will allow both BROWN and the International Brownfields Collaborative to further develop and collaborate.

As the International Brownfields Collaborative continues to expand, its activities may contribute to the dissemination of interdisciplinary approaches and best practices in health-focused and sustainable land reuse across different institutional and geographical contexts. The Collaborative also provides a platform for strengthening international research partnerships, educational cooperation, and knowledge exchange related to military, war, and post-war brownfields.

Conclusion. Colleagues from 15 different countries attended the ARW. During the workshop, our working group expanded into the International Brownfields Collaborative, growing from five to more than 20 members. The Collaborative brought together researchers, public health professionals, planners, educators, and practitioners working in the fields of brownfields redevelopment, environmental security, sustainable development, and public health. Particular importance was given to the participation of representatives from Ukraine, a NATO-partner country currently facing extensive challenges associated with military, war, and post-war brownfields.

During the ARW, one module of the Environmental Health and Land Reuse (EHLR) training was implemented as part of Panel 1 activities. The subsequent adoption of the EHLR training at V. N. Karazin Kharkiv National University as a specialized seminar for graduate students created new opportunities for expanding international educational cooperation and disseminating interdisciplinary approaches to sustainable redevelopment. Another important outcome of the Collaborative was the publication of the 2024 Springer book Achieving Sustainability in Ukraine through Military Brownfields Redevelopment, which presented research findings, case studies, and collaborative initiatives developed within the ARW framework [11]. Several chapters in the volume focus on sustainable land reuse and post-war redevelopment challenges in Ukraine and other participating countries.

The Collaborative also contributed to supporting graduate students and young researchers in the fields of geography, urban studies, tourism, environmental sciences, and spatial planning by creating opportunities for international academic exchange and interdisciplinary research cooperation. Although the Collaborative is still in an early stage of institutional development, its activities demonstrate significant potential for expanding international research and educational cooperation in the field of sustainable brownfields redevelopment.

The experience of the International Brownfields Collaborative demonstrates the growing importance of interdisciplinary international networks in addressing emerging environmental and socio-spatial challenges associated with military, war, and post-war brownfields. The Collaborative highlights the need to integrate public health, environmental security, sustainable development, and resilience-oriented spatial planning into post-war recovery strategies. The findings may also support policymakers and planning institutions in developing integrated strategies for sustainable redevelopment and environmental recovery in conflict-affected regions. Future research should focus on developing integrated frameworks for environmental assessment, public health monitoring, sustainable redevelopment, and resilience-oriented planning in conflict-affected territories.

Поодяка: Ми висловлюємо подяку доктору Мотрії Пошиваник Коділл, директору регіону 5 Агентства з реєстру токсичних речовин і захворювань, за її огляд і внесок історичних даних у цей коментар.
Стаття підтримана грантом № ARW G5666 під назвою «Досягнення сталого розвитку в Україні через реконструкцію військових територій», що фінансується програмою НАТО «Наука заради миру та безпеки».
Внесок авторів: всі автори зробили рівний внесок у цю роботу.
Конфлікт інтересів: автори засвідчують, що, незважаючи на те, що один із авторів статті є членом редакційної колегії цього журналу, процес рецензування, прийняття рішення щодо публікації та редагування проводилися незалежно, без його участі чи впливу; будь-які потенційні конфлікти інтересів були повністю усунені шляхом зовнішнього контролю процесу; автори не мають жодних фінансових чи інших конфліктів; фінансування NATO ARW не використовувалося для підтримки цього рукопису; висновки у цьому звіті належать авторам і не обов'язково відображають офіційну

Acknowledgement: We acknowledge Dr. Motria Poshyvanyk Caudill, the Agency for Toxic Substances and Disease Registry's Region 5 Director, for her review and contribution of historical data to this Commentary.
The article was supported by the grant number ARW G5666, titled "Achieving Sustainability in Ukraine through Military Brownfields Redevelopment", financed through the NATO Science for Peace and Security Program.
Author Contributions: All authors contributed equally to this work.
Conflict of Interest: The authors certifies that, although one of the authors of the article is a member of the editorial board of this journal, the peer review, publication decision, and editorial processes were conducted independently, without their participation or influence. Any potential conflicts of interest were fully mitigated through external oversight of the process. Authors do not have any financial or other conflicts. NATO ARW funding was not used to support this manuscript. The findings and conclusions in this report are those of the authors and do not

позицію Агентства з реєстру токсичних речовин та захворювань.

Декларація про використання генеративного штучного інтелекту: автори підтверджують, що під час підготовки рукопису не використовувалися інструменти штучного інтелекту.

necessarily represent the official position of the Agency for Toxic Substances and Disease Registry.

Declaration of use of generative artificial intelligence: The authors confirm that no AI tools were used during the preparation of the manuscript.

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АНОТАЦІЯ

Браунфілди та деградовані території є характерними для всіх країн світу й становлять важливі екологічні, економічні, соціальні та просторово-планувальні виклики. Особливого значення набувають військові, воєнні та повоєнні браунфілди, що формуються внаслідок збройних конфліктів і потребують комплексних підходів до післявоєнного відновлення. У 2015 році фахівці зі США, Канади, Румунії та України створили Американо-Східноєвропейську робочу групу з браунфілдів, яка стала основою для формування Міжнародного консорціуму з браунфілдів (International Brownfields Collaborative). Метою дослідження є аналіз становлення та розвитку цього консорціуму як міждисциплінарної платформи міжнародного співробітництва у сфері сталого відновлення деградованих територій. Проведення ARW стало поштовхом до створення Міжнародного консорціуму з браунфілдів, який нині об'єднує понад 20 фахівців із 15 країн. До його складу входять науковці, фахівці з територіального планування, екології, громадського здоров'я та сталого розвитку. Консорціум сприяє розвитку міждисциплінарних підходів до ревіталізації браунфілдів через наукові дослідження, міжнародні публікації, воркшопи та освітні програми. Важливим результатом стало впровадження навчального курсу Environmental Health and Land Reuse (EHLR) у Харківському національному університеті імені В. Н. Каразіна, що сприяло розвитку міжнародної академічної співпраці та формуванню компетентностей у сфері сталого розвитку. Досвід діяльності Міжнародного консорціуму з браунфілдів демонструє важливість міждисциплінарних міжнародних мереж для вирішення екологічних, соціально-просторових і медико-санітарних проблем, пов'язаних із військовими, воєнними та повоєнними браунфілдами. Дослідження наголошує на необхідності інтеграції принципів сталого розвитку, екологічної безпеки, громадського здоров'я та просторового планування, орієнтованого на забезпечення стійкості територій, до стратегій післявоєнного відновлення. Отримані результати можуть бути корисними для органів державної влади, установ територіального планування та наукової спільноти під час розроблення комплексних підходів до сталого відновлення територій і екологічної реабілітації регіонів, що постраждали від збройних конфліктів.

ІНФОРМАЦІЯ ПРО СТАТТЮ :

Рукопис надійшов
20 квітня 2026

Отримано після рецензування
22 травня 2026

Затверджено до друку
25 травня 2026

Опубліковано онлайн
30 травня 2026

Ключові слова:

браунфілди; військові браунфілди; воєнні браунфілди; повоєнні браунфілди; забруднення; стале відновлення територій; екологічна безпека; громадське здоров'я; міська стійкість; міжнародне співробітництво.

https://doi.org/10.26565/2410-7360-2026-64-12

UDC 528.88

Development of Algorithms for Remote Evaluation of Chlorophyll «a» in the Water Bodies of the Dniester River Delta Using Sentinel-2 MSI

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ABSTRACT

Problems Statement and Objective. Intensive economic activity in the Dniester River basin and overregulation of its flow via excessive reservoirs provoke eutrophication and deterioration of the water quality affecting ecosystem biodiversity and threatening public health. To achieve sustainable water quality management, it is proposed to use remote sensing (RS) to estimate chlorophyll «a» concentration as a tool for water bodies monitoring. To consider optical properties of these objects and to determine functional dependences, the concentrations calculated with different algorithms based on RS data are compared with field measurements. The main objective of this study is to select and validate the algorithms for remote estimation of chlorophyll «a» concentration in water bodies of the Dniester River Delta using measurements from the Sentinel-2 Multispectral Instrument (MSI).

Data and Methods. Chlorophyll «a» concentrations obtained from the Dniester Delta water bodies from April to September of 2017-2021 have been used. Also, two types of MSI reflectance were used: top-of-atmosphere (TOA) and surface reflectance (SR). During the selection of optimal algorithms, a literature review was conducted. It was decided to select two types of MSI Sentinel-2 spectral band functional combinations. Also, calculations of chlorophyll «a» concentration by the C2RCC (Case 2 Regional Coast Color) processor in SNAP Sentinel Toolbox platform were used.

Results and Discussion. Exponential-type functional dependences were established during development of the selected two-channel and three-channel models. The proposed functional dependences were verified by comparing the calculated values, as well as obtained by the C2RCC processor, with the chlorophyll «a» concentration in the field samples. Comparison showed an advantage of using the TOA coefficients (compared to SR) for both the two-channel and three-channel models: $Rp_{<0.001}$=0.92, MAPE=28.5, RMSE=14.4 mg/m^3 and $Rp<_{0.001}$=0.93, MAPE=27.9, RMSE=14.3 mg/m^3, respectively. An underestimation of the chlorophyll «a» concentration calculated by the C2RCC processor was found.

Conclusions. The functional dependences based on two- and three-channel TOA combinations of the Sentinel-2 satellite's MSI spectral bands have been proposed for calculation of chlorophyll «a» concentration in complex inland waters of the Dniester River Delta and the Dniester Estuary. Manual and semiautomatic filtering of cloudy, mist, cloud shadowed, and aquatic vegetation-covered areas from imagery has been proposed as a mandatory calculation step. Chlorophyll «a» concentration calculation by the C2RCC processor in the C2X-COMPLEX version for turbid inland waters should be assessed critically due to the ongoing development of atmospheric correction algorithms. Nevertheless, analysis of the selected functional dependences for various types of complex waters, combined with improvements to the atmospheric correction module, offers significant potential of the C2RCC processor, which uses trainable neural networks, to be used in remote monitoring of inland and coastal waters.

ARTICLE INFO

Manuscript received 1
9 April 2026

Revised manuscript received
23 May 2026

Manuscript accepted
25 May 2026

Available online
30 May 2026

Keywords:

Dniester River Delta, ecological status of water bodies, chlorophyll «a», remote sensing, Sentinel-2 MSI, C2RCC, atmospheric correction algorithms, functional models.

In cites: Gazyetov Yevgen, Kovalova Nataliia, Medinets Volodymyr (2026). Development of Algorithms for Remote Evaluation of Chlorophyll «a» in the Water Bodies of the Dniester River Delta Using Sentinel-2 MSI. *Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology*, (64), 153–163. https://doi.org/10.26565/2410-7360-2026-64-12



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Introduction

The Dniester River Delta and the Dniester Estuary are transitional water system between the river and the Black Sea. The biotic and abiotic characteristics of these water bodies are constantly influenced by climate change, land use pattern in the catchment area, and the extent of water resource exploitation. Intensive economic activity in the region provokes eutrophication of river water due to enrichment with nutrients caused by constant discharge of agricultural waste and municipal wastewater. Permanent eutrophication and overregulation of the river flow via excessive reservoirs lead to long-term deterioration of water quality, which reduces biodiversity of aquatic ecosystems and the potential for multi-purpose use of water resources, and creates a threat to public health.

Regular spatial and temporal monitoring of the water bodies environmental state is essential for sustainable water quality management under these conditions. Remote sensing (RS) data play a very important role here, offering significant advantages over field monitoring data due to its high spatial resolution, simultaneous coverage of large areas, and data availability. Field monitoring data remain necessary, but in smaller quantities, for verifying RS-based calculations and constructing of empirical models.

A significant number of studies of water bodies using remote sensing have focused on determining the concentration of chlorophyll in water [1, 2, 3], which is used to evaluate an aquatic environment trophic status [4], as well as a quantitative indicator of phytoplankton biomass [5]. However, as shown in [1], when using remote sensing for inland water bodies, an individual approach is required due to the unique optical properties of different aquatic environments. A solution to choose the best functional calculation model could be comparison of RS evaluation of water pigment concentration using different algorithms with the results of field measurements in order to establish a significant relationship.

The main objective of this study is to select and validate an algorithm for remote evaluation of chlorophyll «a» concentrations in water bodies of the Dniester River Delta and the Dniester Estuary using RS data. The following was done for this purpose:

(1) correlation and regression analysis of chlorophyll «a» concentrations determined in water samples in laboratory and calculated using various functional models based on Sentinel-2 satellite Multispectral Instrument (MSI) measurements;

(2) validation and revealing of the specific features of the MSI data-based algorithms using for construction of chlorophyll «a» concentrations spatial distribution in the studied water bodies.

Material and methods

To achieve the objective, field data on chlorophyll «a» concentration in the water surface layer of the Dniester Estuary, the Dniester River and Lake Tudorovo, obtained by the Regional Centre for Integrated Environmental Monitoring (RCIEM) team of Odesa National I.I. Mechnikov University (ONU) in April-September 2017-2021 under the national research projects and the PONTOS International Project [6] were used (Figure 1).



Fig. 1. A complete set of water sampling points from 2017 to 2021 in the Dniester River Delta and the Dniester Estuary, used in this study

Surface water samples for chlorophyll determination were collected at fixed (±10 m) coordinates directly into sampling containers above optically deep water, i.e. where the water depth was lower than its transparency. During sampling additional parameters, such as temperature, electrical conductivity, water transparency, depth, and others, were measured (Table 1). Within three to four hours the samples were delivered to the RCIEM laboratory, where phytoplankton cells were concentrated through membrane filters and photosynthetic pigment concentrations were determined using the YENWAY-6300 spectrophotometer.

The time period during which the data were collected covered significant part of the natural seasonal and interannual variability of chlorophyll «a» in the inland waters of the Dniester River Delta enabling us to state temporal representativeness of the field data used.

To remotely determine photosynthetic pigments' concentrations in the Dniester Estuary, the Dniester

Table 1

Statistical characteristics of chlorophyll «a» concentrations and other parameters measured during the RCIEM surveys in the Dniester Estuary, the Dniester River and the Lake Tudorovo in 2017–2021

Parameter	Mean	Standard deviation	Median	Min	Max	Dataset Length
Chl «a», mg/m^3	41.7	34.3	34.3	5.0	151.5	50
Depth, m	2.2	0.9	1.9	1.2	5.8	50
Transparency, m	0.5	0.2	0.5	0.2	0.8	50
Temperature, °C	21.8	5.3	23.3	11.9	29.3	50
Conductivity, mSm	1.81	2.15	0.68	0.45	8.85	50

River, and the Lake Tudorovo, high-resolution multispectral sensor (MSI) measurements of the Sentinel-2 satellite for 2017–2021 (hereinafter referred to as images) were used. The MSI produces measurements in 13 spectral bands with spatial resolution of 10 to 60 m per pixel, which allows to obtain an information even for relatively small water bodies. Two types of the MSI products were taken from open sources [7]:

– first level of processing (Level-1C): solar radiation reflectance coefficients at the top of the atmosphere (TOA - Top-of-atmosphere reflectance);

– second level of processing (Level-2A): atmospherically corrected solar radiation reflectance coefficients at the bottom of the atmosphere (BOA - Bottom-of-atmosphere reflectance), now referred to as Surface Reflectance (SR).

In this work, the MSI sensor products from the Copernicus database [7], version 2023, were used. A similar work was conducted [6] in the framework of the PONTOS International Project in 2021, but at that time the Sentinel-2 satellites images of previous versions were used. With the new, latest version of the images used in this work the results of the chlorophyll concentration calculation were significantly different from those presented in [6].

The MSI data and the field samples selection criteria were as follows (Table 2):

– the availability of a field sample of photosynthetic pigments, collected in the spatial coverage of the image, on the day and the closest possible time of the satellite overflight (less than 4 hours difference);

– the complete absence of clouds, cloud shadows, and mist on the images above the field sampling points to prevent from potential errors in indirect methods of pigment concentration calculation.

According to the literature data [3, 8, 9], remote (satellite) determination of chlorophyll «a» concentration was initially used for the open ocean waters: the blue and green spectral bands were used in indirect empirical and semi-analytical algorithms [10]. The algorithms are based on dependences between reflectance in different parts of the spectrum and the Inherent Optical Properties (IOP) of water, the coefficients of total absorption and backscattering of solar radiation.

Empirical dependences estimate pigments using equation of regression between sample concentration and satellite-derived reflectance [3, 11]. These methods account for regional variability of water properties and have been used by the NASA to obtain chlorophyll «a» concentration with Coastal Zone Color Scanner (CZCS) [10].

Semi-analytical algorithms allow pigment concentrations to be obtained by solving equations from radiative transfer theory [10, 12], separating various components influencing color in natural water and accounting separately

Table 2

List of the Sentinel-2 images for 2017-2021 used for this study

№	Image ID	Date
1	S2B_MSIL1C_20170717T090019_N0205_R007_T35TQM	17.07.17
2	S2A_MSIL1C_20180717T085601_N0206_R007_T35TQM	17.07.18
3	S2A_MSIL1C_20190712T085601_N0208_R007_T35TQM	12.07.19
4	S2B_MSIL1C_20190717T085609_N0208_R007_T35TQM	17.07.19
5	S2B_MSIL1C_20200718T084559_N0209_R107_T35TQM	18.07.20
6	S2B_MSIL1C_20210424T084559_N0300_R107_T35TQM	24.04.21
7	S2A_MSIL1C_20210611T085601_N0300_R007_T35TQM	11.06.21
8	S2A_MSIL1C_20210718T084601_N0301_R107_T35TQM	18.07.21
9	S2A_MSIL1C_20210820T085601_N0301_R007_T35TQM	20.08.21
10	S2A_MSIL1C_20210929T085751_N0301_R007_T35TQM	29.09.21

for the absorption of solar radiation by water, phytoplankton, dissolved organic matter, and non-algal particles.

In shallow, productive, optically complex coastal and inland waters the absorption of phytoplankton pigments in the blue spectral region overlaps and prevents the unambiguous use of this area in calculations. Significant uncertainty in these waters is caused by the dominance of suspended organic detritus and colored dissolved organic matter (CDOM) in the optics of the water column [13].

There are algorithms based on the reflectance peak around 700 nm (red spectral region) and the assumption that the specific absorption coefficient and the fluorescence quantum yield of chlorophyll "a" remain constant [13] for quantitative estimation of chlorophyll concentration in optically complex waters, which also adds uncertainty. In [14] an empirical three-band reflectance model to estimate chlorophyll «a» concentration in turbid productive waters was presented, and in [15] it was developed, which was originally intended for estimation of pigment content in terrestrial vegetation. According to [15], in turbid inland and coastal waters, the models combining spectral reflectance bands should be used, taking into account the absorption band of chlorophyll «a» in the red spectral region and the fluorescence emission of chlorophyll «a» at 685 nm. Sources of uncertainty in this model are the taxonomic composition of phytoplankton, light conditions, nutritional status, and water temperature.

To select the optimal algorithm for evaluating of chlorophyll «a» concentration in turbid productive waters using the Sentinel-2 images we have analyzed, using literature sources, combinations of reflectance coefficients in the 660–753 nm range for the following sensor types: MODIS – Moderate Imaging Spectrometer, MERIS – Medium Resolution Imaging Spectrometer, SeaWiFS – Sea-viewing Wide Field-of-view Sensor, Ocean Optics USB2000 radiometer, and AISA airborne imaging spectrometer. Then, based on existing studies for various sensors listed in Table 3, two types of spectral band combinations from the MSI Sentinel-2 sensor set were selected for development:

- Two-channel model - [Chl «a»] ~ $R_{704\pm15}/R_{665\pm31}$,
- Three-channel model - [Chl «a»] ~ $R_{740\pm14}/(R_{665\pm31}+R_{704\pm15})$,

where [Chl «a»] – concentration of chlorophyll «a» in the surface layer of water; R(λ) – reflectance coefficients for waves of different lengths (λ).

Another indirect method used in this work is the calculation of chlorophyll «a» in the C2RCC (Case 2 Regional Coast Colour) processor [18], which uses trainable neural networks. The algorithmic foundations of the processor were established by Schiller and Dörffer [19]. The latest modification, the C2X-COMPLEX (C2XC) processor, which showed good results in complex waters [20], was used in this work.

The processor core is a 5-component IOP model of water that takes into account absorption by pigment, detritus, yellow matter, and scattering by "white particles" (lime deposits) and "typical sediment" [18]. The average absorption and scattering spectra of particles in water in the processor are calculated using dataset from the NOMAD database [21], based on a numerous marine field measurements set.

The C2RCC was designed to calculate chlorophyll concentration, Total Suspended Matter (TSM) and other surface water characteristics using data from sensors on the MERIS, Sentinel-3 (OLCI), Sentinel-2 (MSI), and other satellites. The processor is available on the European Space Agency's SNAP Sentinel Toolbox [22] platform as open-source software. To obtain more accurate results, the processor uses real-world parameters of the aquatic environment, such as salinity and temperature, as well as certain atmospheric characteristics, such as pressure and ozone concentration.

The C2RCC processor is equipped with a built-in atmospheric correction neural network: the

Table 3

Examples of models and fundamental dependences for remote determination of chlorophyll «a» concentration in water for different sensors

Source	Functional dependences forms
Kallio et al., 2003 [16]	Two-channel model (for AISA airborne imaging spectrometer): [Chl «a»] = a * ($R(\lambda_1)$ / $R(\lambda_2)$) + b, where λ_1 = 700–710 nm, λ_2 = 660–665 nm
Dall'Olmo & Gitelson, 2005 [15]	Three-channel model (for Ocean Optics USB2000 radiometer): [Chl «a»] ~ [$R^{-1}(\lambda_1)$ - $R^{-1}(\lambda_2)$] * $R(\lambda_3)$, where: λ_1 = 673 (or 665) nm, λ_2 = 710 nm, λ_3 = 740 nm
Gitelson et al., 2007 [17]	Two-channel model (for SeaWiFS, MODIS, MERIS): [Chl «a»] ~ $R^{-1}(\lambda_1)$ * $R(\lambda_3)$, where: λ_1 = 668–672, λ_3 = 713–722 nm
Gilerson et al., 2010 [13]	Two-channel model (for MERIS): [Chl «a»] = [35.75 * $R(\lambda_1)$ / $R(\lambda_2)$ −19.30]$^{1.124}$, where: λ_1 = 708 nm, λ_2 = 665 nm
Gilerson et al., 2010 [13]	Three-channel model (for MERIS): [Chl «a»] = [113.36 * R(λ3) / (R(λ1) + R(λ2)) + 16.45]$^{1.124}$, where: λ_1 = 708 nm, λ_2 = 665 nm, λ_3 = 753 nm

"water" part of the processor receives reflectivity signals from the "atmospheric" part as an input. However, no standard atmospheric correction model exists for inland waters: all existing approaches have limitations. At the same time, atmospheric correction of optical satellite data is a critical step, as the reflectance measured as the top-of-the-atmosphere (TOA) signals must be correctly converted to water reflectance in the bottom of the atmosphere (SR) before practical use. Otherwise, poor atmospheric correction becomes the largest source of error and uncertainty in satellite products based on reflectivity.

For calculations with the proposed functional models and the C2RCC processor the reflectance coefficients R(λ) for different spectral regions obtained from Sentinel-2 MSI images with processing levels Level-1C and Level-2A were used. The original images were modified in the SNAP environment: (1) cropping the image coverage area by the study area in order to minimize the calculation time; (2) changing the spatial resolution of the images to 20 m per pixel for all spectral bands.

TOA and SR reflectance coefficients from the Sentinel-2 MSI images and chlorophyll «a» concentration calculated by the C2XC were extracted in SNAP in 3x3-pixel windows, localized at field sampling points in the center. From these nine-pixel windows cells, the cells in which the calculated values of chlorophyll «a» concentration exceeded the 50% of those determined in the field samples were manually discarded. Cells with detected vegetation, mist, and shadow were also rejected. This cell rejection process is based on the fact that the C2XC automatically checks cloud cover using Sentinel-2 MSI spectral band 8 using preset thresholds.

For the remaining cells of the nine-pixel windows the median values of both chlorophyll «a» concentration calculated using the C2XC algorithm and the TOA and SR reflectance coefficients from the Sentinel-2 MSI products (Level-1C and Level-2A, respectively) modified to 20-meter resolution were used. The median values of the nine-pixel windows were used to minimize the influence of cells with wrong outliers.

Results and discussion

In the process of the two-channel and three-channel models development, the exponential-type functional dependences were established, as shown in Figs. 2-5. Calculations of chlorophyll «a» concentration based on the derived functional dependences are shown next to the model graphs in Figs. 2a-5a.

Graphical and numerical results of calculations of chlorophyll «a» concentration in the surface water layer by the C2XC processor in the SNAP are shown in Fig. 6.

A comparison of the results calculated using different algorithms was analyzed for their correspondence to field data. For each functional model the statistical estimates were calculated: the correlation coefficient R, the mean absolute percentage error (MAPE) (1), and the root mean square error (RMSE) (2) (Table 4):

$$MAPE = 100\% \cdot \frac{\sum_{i=1}^{N} \left| \frac{x_i - y_i}{x_i} \right|}{N} \quad (1);$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (x_i - y_i)^2} \quad (2),$$

where x_i – measured, and y_i – calculated chlorophyll «a» concentration for i-point; N – the quantity of comparing pairs.

MAPE was chosen because it allows for comparison of algorithms regardless of the

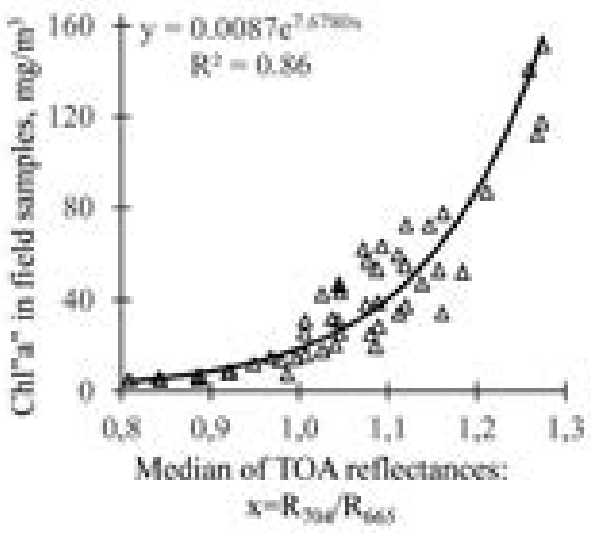


Fig. 2. Functional dependence of chlorophyll «a» concentration on two-channel TOA combination

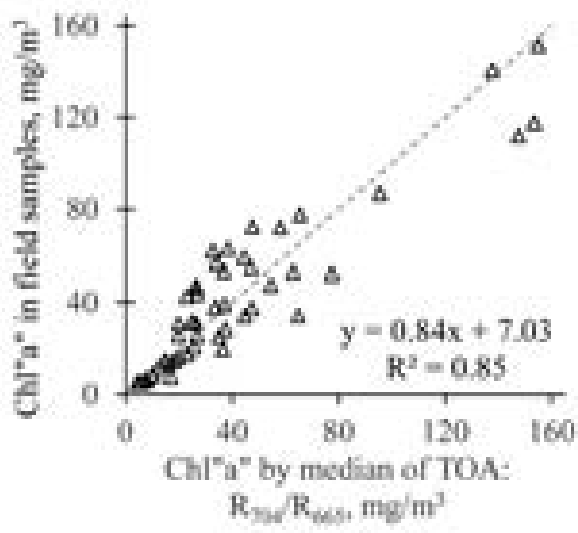


Fig. 2a. Scatter plot of calculated (TOA, two-channel model) and measured chlorophyll «a» concentration

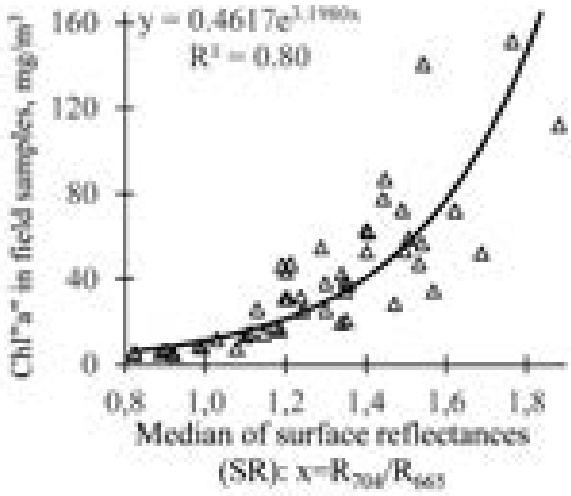


Fig. 3. Functional dependence of chlorophyll «a» concentration on two-channel SR combination

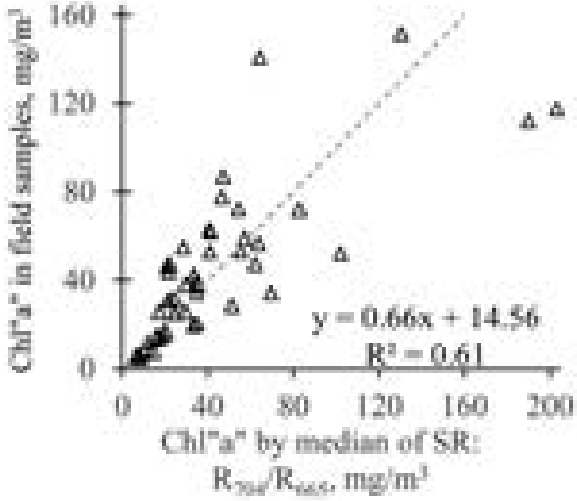


Fig. 3a. Scatter plot of calculated (SR, two-channel model) and measured chlorophyll «a» concentration

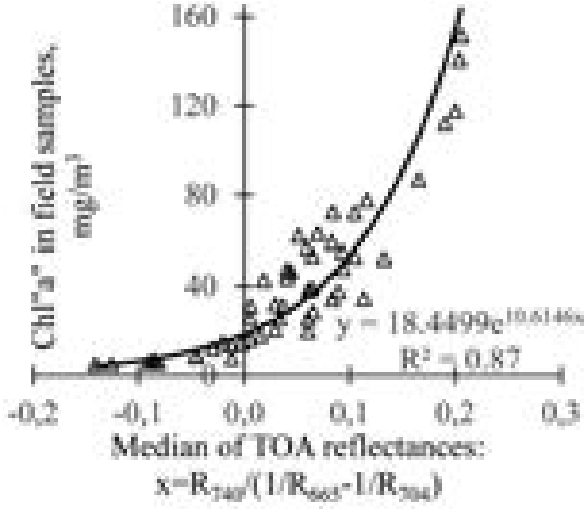


Fig. 4. Functional dependence of chlorophyll «a» concentration on three-channel TOA combination

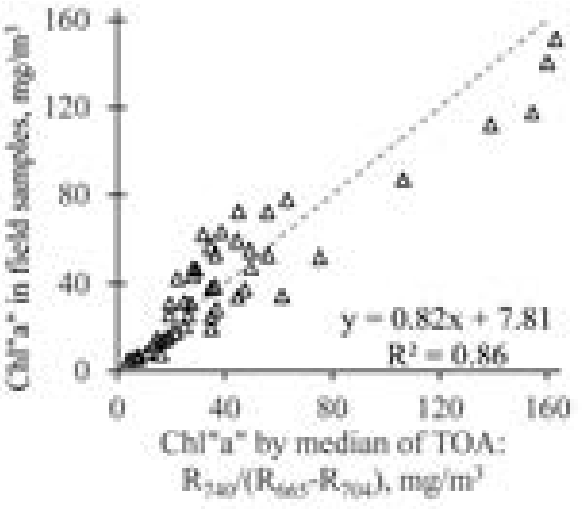


Fig. 4a. Scatter plot of calculated (TOA, three-channel model) and measured chlorophyll «a» concentration

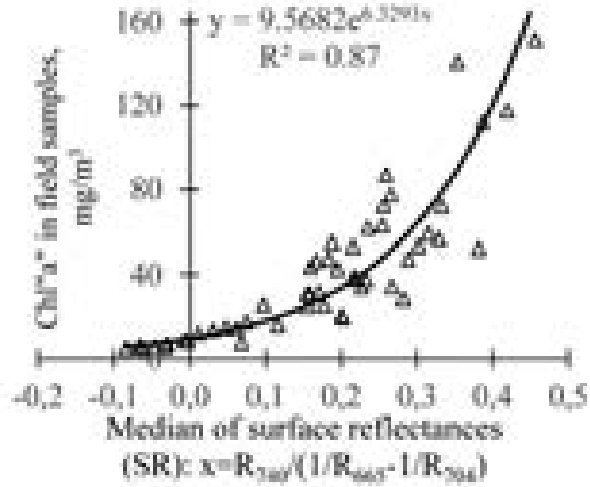


Fig. 5. Functional dependence of chlorophyll «a» concentration on three-channel SR combination

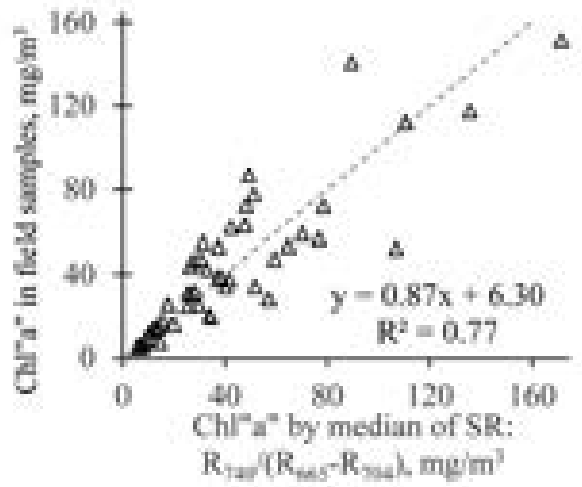


Fig. 5a. Scatter plot of calculated (SR, three-channel model) and measured chlorophyll «a» concentration

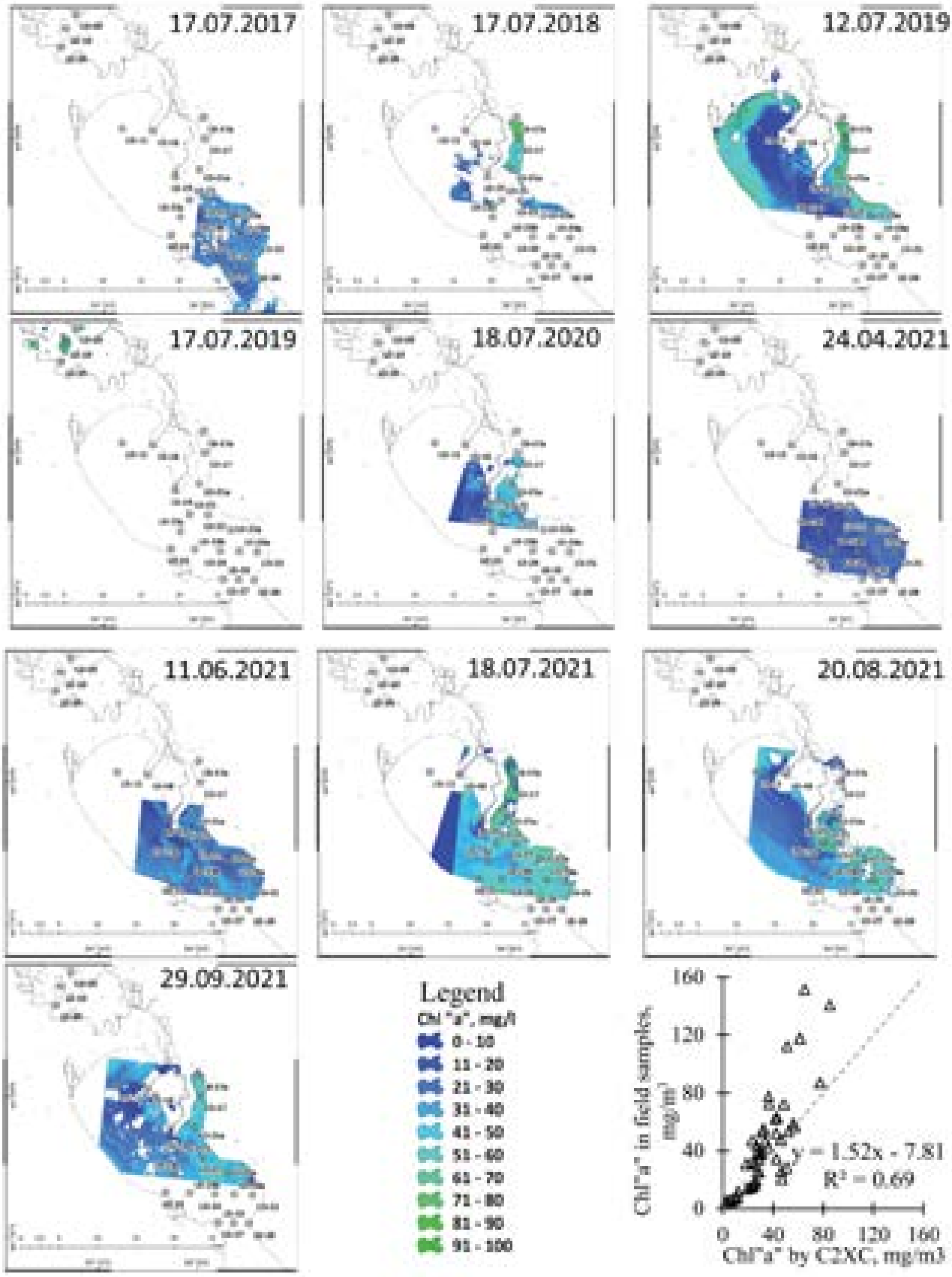


Fig. 6. The C2XC calculated chlorophyll «a» concentration in the Dniester River Delta and estuary in 2017-2021 (on the background of planned sampling points) and the summary scatterplot of calculated (C2XC) and measured concentrations

Table 4

Statistical assessments of accuracy of the chlorophyll «a» concentration calculating based on Sentinel-2 MSI data using different algorithms

Algorithm of Calculation	R (p< 0.001)	MAPE	RMSE, mg/m3
Two-channel model by TOA reflectance	0.92	28.5	14.4
Two-channel model by SR reflectance	0.78	27.8	16.8
Three-channel model by TOA reflectance	0.93	27.9	14.3
Three-channel model by SR reflectance	0.88	35.0	25.2
The C2XC algorithm	0.83	33.6	23.1

selected concentration ranges. Of all the calculation methods considered, those yielding the lowest MAPE and RMSE, as well as the highest correlation coefficients, were selected. This allowed to take into account the strength of linear relationship and the dispersion in the scatterplots of calculated and measured chlorophyll «a» concentrations across the entire range of values, i.e. from 5.0 to 151.5 mg Chl «a»/m^3.

As noted above, the reflectance coefficients R(λ) by the Sentinel-2 MSI the processing levels Level-1C and Level-2A (i.e. TOA and SR) were used during development of the functional dependence. Pairwise comparison of data series has demonstrated the advantage of the TOA coefficients (in contrast to the SR) using for both two-channel and three-channel models (Table 4). This is especially clearly seen from the correlation coefficients and RMSE's.

A possible explanation for this is the quality of atmospheric correction by the Sen2Cor processor, developed by Telespazio VEGA Deutschland GmbH [23, 24]. This processor performs correction of Sentinel-2 Level-1C (TOA) products to account for the influence of the atmosphere and produces Level-2A (SR) products. Two main Sen2Cor modules are designed to process Level-1C input data: the scene classification module (SCL) and the atmospheric correction module (AC), which deals with the absorption and scattering of light by gas molecules and aerosol particles in the atmosphere. The SCL module, using threshold tests based on TOA coefficients, classifies cirrus and other clouds, their shadows, snow, vegetation, and water. This classification and masking are then applied in the AC module with atmospheric conditions stored in look-up tables (LUTs), which are in turn calculated using libRadtran [25], a library of functions and programs for calculating solar and thermal radiation transport in the Earth's atmosphere. The LUTs were calculated from the spectral responses of Sentinel-2A and Sentinel-2B [24] for a range of sensor and solar geometries, surface elevations, and a variety of atmospheric parameters. AC reads the LUT corresponding to the geographic and spatial location and performs parameter interpolation.

To account for the influence of aerosols in the atmosphere libRadtran suggests to use a basic list of aerosol types with additional specific parameters: rural, urban, marine, desert, fog, winter/summer atmosphere, ozone concentration, visibility, and climate characteristics. However, interpolation is not supported for the aerosol type also included in the LUT, which may lead to errors in atmospheric correction, as our study area is located less than 50 km from the Black Sea coast.

Furthermore, the Sen2Cor processor [24]:

– is not intended for overwater or coastal applications;

– does not contain modules for correcting water surface effects (e.g., sun glares in rough seas);

– does not estimate the optical thickness of aerosols and water vapor above the water surface.

The use of the Sen2Cor processor over water is possible, but requires the use of aerosol optical thickness and water vapor concentration over the nearest land surface, which also affects the result of atmospheric correction over the studied water bodies of the size of the Dniester Estuary and the floodplains of the Dniester River Delta.

The concentrations of chlorophyll «a» calculated by C2XC are clearly underestimated compared to other algorithms (Table 4). This may be due to several factors. Firstly, the C2RCC processor uses only the built-in atmospheric correction of the Sen2Cor processor [24], which operates according to a simplified libRadtran scheme [25]. Secondly, the aerosol optical thickness (AOT) is derived according to a simplified scheme of the method [26] with the aerosol type fixed for land. Evaluating the obtained results, one should agree with [20] that for coastal and inland waters, the problem of eliminating the contribution of atmospheric components (gases, aerosols) in the reflected signal, along with such interference as sun glares, proximity to land, and aquatic vegetation, requires further development of the C2RCC processor in the C2X-COMPLEX version in the form of a more detailed adjustment of the atmospheric correction algorithms and the development of a standardized approach.

It should also be noted that the C2RCC was developed based on the 16 spectral channels of the

MERIS spectrometer [19], whose characteristics were precisely tailored to capture the dynamics of the concentration and composition of phytoplankton pigments and yellow matter. The latest versions of C2RCC, including C2X-COMPLEX, are an adaptation of the original Case 2 Regional Coast Color design to sensors with different sets, characteristics, and bandwidths, such as the Sentinel-2 and Landsat-8 sensors.

Conclusions

To obtain a satisfactory (correlation coefficient of up to 0.93) estimate of chlorophyll «a» concentration in complex inland waters of the Dniester River Delta and the Dniester Estuary based on Sentinel-2 satellite MSI data, we propose using exponential-type empirical functional dependencies for two- and three-channel TOA spectral band combinations, i.e. based on solar radiation reflectivity at the top of the atmosphere (without atmospheric correction). The difference in calculation accuracy between the two- and three-channel combinations was found to be insignificant, with a slight advantage for the three-channel model.

A mandatory step in preparing TOA reflectance coefficients for use in the proposed functional relationships is the removal of water areas covered by clouds, mist, cloud shadows, and aquatic vegetation from Sentinel-2 images. Thus, manual and semiautomatic preparation of Sentinel-2 MSI data remains a significant element for use in the proposed algorithms.

The calculations of chlorophyll «a» concentration by the C2RCC processor in the C2X-COMPLEX version for turbid inland waters should be assessed critically due to the ongoing development of atmospheric correction algorithms. However, the analysis of the selected functional dependencies for various types of complex waters, combined with the improvement of the atmospheric correction module offers significant potential for the C2RCC processor, which uses trainable neural networks, to automate remote monitoring of inland and coastal waters.

Подяка: Автори висловлюють вдячність співробітникам Регіонального центру комплексного екологічного моніторингу Одеського національного університету імені І.І. Мечникова, які брали участь у зборі польових даних у 2017–2021 роках.

Внесок авторів: всі автори зробили рівний внесок у цю роботу
Конфлікт інтересів: автори повідомляють про відсутність конфлікту інтересів.
Декларація про використання генеративного штучного інтелекту: автори підтверджують, що під час підготовки рукопису не використовувалися інструменти штучного інтелекту.

Acknowledgements. The authors express their gratitude to the staff of the Regional Centre for Integrated Environmental Monitoring of the Odessa National I.I. Mechnikov University who participated in collecting the field data in 2017–2021. Лит-ра №7 №22 (accessed November 13, 2024).
Author Contributions: All authors contributed equally to this work.
Conflict of Interest: The authors declare no conflict of interest.

Declaration of use of generative artificial intelligence: The authors confirm that no AI tools were used during the preparation of the manuscript.

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ISSN 2410-7360 (Print)
ISSN 2411-3913 (Online)
Вісник Харківського національного університету імені В.Н. Каразіна Серія «Геологія. Географія. Екологія» 2026 64 С. 153–163
Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology 2026 64 153–163

Розробка алгоритмів дистанційної оцінки хлорофілу «а» у внутрішніх водах дельти річки Дністер з використанням даних Sentinel-2 MSI

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АНОТАЦІЯ

Господарська діяльність у басейні річки Дністер та зарегульованість водного стоку провокують евтрофікацію та погіршення якості води, що впливає на біорізноманіття екосистем та є загрозою для здоров'я населення. З метою стійкого управління якістю води пропонується дистанційне зондування Землі для оцінки концентрації хлорофілу «а». Для урахування оптичних властивостей вод та визначення функціональної залежності застосовано порівняння розрахункових концентрацій з результатами польових вимірів. Метою роботи є підбір та обґрунтування алгоритмів для дистанційної оцінки концентрації хлорофілу «а» у водоймах дельти річки Дністер за даними Multispectral Instrument (MSI) супутника Sentinel-2.

Використані концентрації хлорофілу «а» у водоймах дельти річки Дністер, що отримані у 2017-2021 рр. Використані коефіцієнти відбиття радіації з MSI двох типів: TOA (Top-of-atmosphere reflectance) та атмосферно відкориговані SR (Surface Reflectance). При підборі алгоритмів проаналізовано літературу, на основі чого відібрані два типи комбінацій спектральних смуг MSI. Застосовувався розрахунок концентрації хлорофілу «а» процесором C2RCC на базі SNAP Sentinel Toolbox.

Для відібраних двохканальної та триканальної моделей встановлено функціональні залежності експоненційного типу. Верифікація залежностей проводилася порівнянням розрахункових і отриманих C2RCC величин з польовими концентраціями хлорофілу «а». Порівняння показало перевагу використання даних TOA (порівняно з SR) як за двоканальною, так і за триканальною моделями: $Rp_{<0,001}$=0.92, MAPE=28.5, RMSE=14.4 мг/м^3 і $Rp_{<0,001}$=0.93, MAPE=27.9, RMSE=14.3 мг/м^3 відповідно. Встановлено заниження розрахованих C2RCC величин.

Для розрахунків концентрацій хлорофілу «а» у водоймах дельти річки Дністер запропоновано двоканальні та триканальні TOA-моделі за спектральними смугами MSI Sentinel-2. Розрахунки концентрації хлорофілу «а» процесором C2RCC для вказаних вод пропонується оцінювати критично через наявні алгоритми атмосферної корекції. Тим не менш, аналіз підібраних залежностей у поєднанні з поліпшенням атмосферної корекції дає процесору C2RCC перспективи для автоматизації дистанційного моніторингу.

ІНФОРМАЦІЯ ПРО СТАТТЮ :

Рукопис надійшов
19 квітня 2026

Отримано після рецензування
23 травня 2026

Затверджено до друку
25 травня 2026

Опубліковано онлайн
30 травня 2026

Ключові слова:

дельта річки Дністер, екологічний стан водойм, хлорофіл «а», дистанційне зондування, Sentinel-2 MSI, C2RCC, алгоритм атмосферної корекції, функціональні моделі.

https://doi.org/10.26565/2410-7360-2026-64-13

UDC 551.509.324

Characteristics of the contemporary spatiotemporal distribution of atmospheric precipitation in the northeastern part of the Lesser Caucasus region

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ABSTRACT

Problem definition. Global warming observed on Earth in recent times is manifested with numerous impacts in mid-latitude regions. The rise in air temperature affects the long-term dynamics of many climatic elements. Consequently, the potential increase in evaporation leads to a reduction in precipitation, which in turn results in decreased freshwater resources and an expansion of health-related risks.
Formulation of the purpose. The purpose of the study is to determine the contemporary spatiotemporal distribution characteristics of atmospheric precipitation in the northeastern part of the Lesser Caucasus region, as well as the effects of climate changes on the long-term precipitation amounts, based on the initial precipitation data for the period 1961-2023.
Research methods. The analyses utilized precipitation data (monthly, seasonal, annual, and long-term) from six hydrometeorological stations operating in this region during the specified period. The study was conducted using mathematical-statistical, cartographic, and physical methods. To determine the spatial distribution pattern, the variation of annual precipitation amounts with elevation was mapped using GIS technology.
The main material. The results of the study indicate that 65% of the annual precipitation occurs during the warm period, while 35% falls in the cold period of the year. In the region, precipitation amounts increase from the lowlands toward the high mountains. Precipitation, which rises up to the upper boundary of the mid-mountain zone, tends to decrease again above approximately 2800 m. The period when precipitation decreases most in the region corresponds to June-September, during which the demand for drinking water reaches its maximum level. In the multi-year period, 90% of the 10 years with lower precipitation occurred after 1995. However, during that period, an increase in extreme precipitation amounts was recorded. This confirms that the majority of the annual precipitation occurred during such events, while drought conditions expanded during other phases of the year.
Conclusions. The long-term average of atmospheric precipitation in the northeastern part of the Lesser Caucasus region (1991-2023) was 451 mm, which is 15% (71 mm) lower than the norm (1981-2010). Maximum precipitation is recorded primarily in Gadabay (up to 1000 mm). The wettest period in the region occurred between 2001 and 2010, while the driest period was after 2010. The sharp decrease in precipitation during

ARTICLE INFO

Manuscript received
12 March 2026

Revised manuscript received
17 April 2026

Manuscript accepted
25 May 2026

Available online
30 May 2026

Keywords:

Global warming, precipitation amount, multiannual variability, monthly maximum precipitation, mean sliding quantity, GIS technology, recurrent precipitation amount, difference integral, Lesser Caucasus region.

In cites: Huseynov Jamal, Suleymanov Mahmud, Huseynova Turana, Guliyev Mahammad (2026). Characteristics of the contemporary spatiotemporal distribution of atmospheric precipitation in the northeastern part of the Lesser Caucasus region. *Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology*, (64), 164–175. https://doi.org/10.26565/2410-7360-2026-64-13

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summer significantly affects crop cultivation and horticulture in the lowlands, as well as hay farming and livestock breeding in the mountainous areas. It is recommended to plant drought-resistant crops and to use modern irrigation technologies (sprinkler and drip systems) in agriculture. Determining the contemporary spatiotemporal distribution of precipitation in this region is essential for climate change mitigation, adaptation strategies, and the assessment of alternative energy sources.

Introduction

The formation of water resources on Earth is regulated by the large and small water cycles. In each of these cycles, the primary driving factors are evaporation, cloud formation, and precipitation [17, 18]. Atmospheric circulation, latitude, relief and orography, proximity to water basins, origin of air masses, temperature regime, and surface characteristics play a crucial role in the uneven distribution of precipitation over the Earth's surface [9, 16].

The amount of atmospheric precipitation varies over time. These variations manifest seasonally throughout the year and on a multi-year scale under the influence of global factors. Nevertheless, differences exist between seasonal and long-term (multi-year) variations [4, 15, 21, 23].

In recent years, with the rise in global temperatures, changes have been observed in the characteristics of the main factors influencing precipitation, with the exception of latitude [2, 5].

Onyutha (2020) found that, compared to 1961-1990, the frequency of extreme precipitation events in various regions of East Africa has increased in recent decades [14]. Elizbarashvili et al. (2025) showed that, using data from 63 meteorological stations for 1950-2022, higher temperature anomalies were detected in high-mountain and subalpine zones. Their study also indicated statistically significant trends, including increased precipitation during the cold season in humid regions and decreased spring precipitation in arid areas [3].

Huseynov et al. (2025) observed a decrease in precipitation on the southern slopes of the Greater Caucasus from 2011 to 2024 in all months except January, March, and May. Consequently, the reduction in precipitation during spring and summer overlaps with the growing season of agricultural crops [6].

The Republic of Azerbaijan stands out among other countries in the South Caucasus, a region where the effects of global warming are particularly pronounced, due to its physical-geographical location [10]. The complexity of the country's relief limits the possibility of conducting comprehensive climate studies across the entire territory; therefore, investigating its constituent regions separately is considered a significant approach [4, 11, 15].

In Azerbaijan, the first comprehensive classification of the surface distribution of precipitation in the southern and southeastern parts of the Lesser Caucasus region was carried out by A.M. Shikhlinski and A.A. Madatzada [1]. In subsequent years, numerous researchers-including N. Sh. Huseynov, F. A. Imanov, R. N. Mahmudov, Surxay H. Safarov, Said H. Safarov, A. S. Mammadov, Kh. Sh. Rahimov, U. R. Taghiyeva, Y. J. Hadiyev, J. S. Huseynov, and others-have conducted extensive studies to determine changes in various precipitation characteristics under the influence of climate change.

In recent years, the effects of climate change on air temperature have been established in the northeastern part of the Lesser Caucasus region. Specifically, compared to 1961-1990, air temperature in the region increased by 1.1 °C during 2006-2020, and compared to 1981-2010, it increased by 1.1 °C during 2011-2023. These changes necessitate a re-evaluation of the contemporary characteristics of atmospheric precipitation in this region [6, 7].

The contemporary state of atmospheric precipitation and the specific effects of climate change on precipitation in the northeastern part of the Lesser Caucasus region have not been extensively studied in previous research. Additionally, the increase in hydrometeorological time series and the recording of new temperature extremes during 2011-2024 necessitate an assessment of their impact on precipitation amounts in the region.

The aim of this study is to determine the contemporary spatiotemporal distribution characteristics of atmospheric precipitation in the northeastern part of the Lesser Caucasus region under the influence of climate change, based on initial precipitation data for 1961-2023.

Materials and methods. The study utilized precipitation data from 1961-2023 collected at six hydrometeorological stations under the National Hydrometeorological Service in the northeastern Lesser Caucasus region: Dashkasan, Goygol, Gadabay, Shamkir, Agstafa, and Ganja. The key characteristics of these stations are presented in Table 1. Primary data were obtained from the Ministry of Ecology and Natural Resources, the State Statistical Committee, and periodic scientific publications [4, 5, 21, 22].

To assess the most recent regional impacts of climate change, we conducted a comparative analysis of precipitation indices between the WMO-recommended climate normal period (1981-2010) and the recent period (2011-2023)

Table 1

Main characteristics of hydrometeorological stations

Station	Elevation, m	Observation periods used at work, year	Climate norms:Precipitation amount (1981-2010), mm
Dashkasan	1614	1961-2023	666
Goygol	1585	1961-1999, 2005-2023	608
Gadabay	1480	1961-2023	699
Shamkir	404	1961-2023	298
Agstafa	331	1961-2023	372
Ganja	312	1961-2023	269

[19, 20]. Additionally, we quantified the annual frequency distribution of precipitation events across different intensity thresholds (< 10 mm, 11-20 mm, 21-30 mm, 31-40 mm, 41-50 mm, 51-60 mm, 61-70 mm, and >70 mm) expressed as percentage occurrence.

Multiple methods exist for analyzing precipitation dynamics across different time periods [8, 12, 15]. However, conventional approaches like graphical representations of annual precipitation and trend curves often prove inadequate due to the high variability inherent in this stochastic variable, making it challenging to discern multidecadal tendencies. Therefore, modern analytical techniques-articularly moving averages and anomaly integral curves-are employed in atmospheric precipitation studies.

For long time series of random variables, sharp deviations in the instantaneous time phase (individual years) can distort the trend, so a moving average is commonly used to smooth the curve. A 3-year moving average reflects short-term fluctuations (interannual variability), while a 5-year moving average provides an optimal balance. Although it shows the trend, it does not fully capture long-term variability. A 10-year moving average, however, better represents the effects of climate change while masking local variations. Therefore, this study uses 10-year moving averages [7, 13]. The moving average is calculated using the following formula (1):

$$XA_k = \frac{1}{n}\Sigma_{i=0}^{n} x_{k-i} \qquad (1)$$

Here, (XA_k) is the moving average for year (k), (n) is the interval length (10 years), and (x) represents the precipitation value for the current year.

To monitor the long-term dynamics of atmospheric precipitation and assess the representativeness of the series, difference-integral curves are also employed. In the analyses, graphs featuring these difference-integral curves have been constructed. The difference-integral is defined by the following formula (2) [7].

$$= \frac{(\Sigma K_i\text{-}1)}{Cv} \qquad (2)$$

Here, *fi* represents the difference-integral, and *Ki* is the ratio of the annual precipitation amount (*Qi*) to the long-term (1991-2023) mean precipitation (*Qor*) of the series. In the formula, *Ki* equals *Qi*/*Qo**r*.

To determine the spatiotemporal distribution patterns of atmospheric precipitation, the analysis employed mathematical-statistical, physical, and cartographic methods. The resulting graphs, tables, and histograms were generated using MS Excel, while the map was created in ArcMap (part of the ArcGIS software suite). Statistical calculations were performed using the StokStat program.

Discussion

The northeastern part of the Lesser Caucasus region is located in the northwestern section of the republic. The area features a combination of mountainous and flat terrain. The primary landforms include the mountain ranges of the Lesser Caucasus-Shahdag, Qashlur, Bulagdag, Pant, and Murovdag-as well as the Ganja-Gazakh plain. The highest peaks above sea level are Shahdag (2901 m), Gochadag (3318 m), Greater Hinaldag (3367 m), and Gamishdag (3927 m). A significant portion of the region lies above the annual snow line. The rivers in the area primarily belong to the Kura River basin, with groundwater, rainfall, and snowmelt playing a crucial role in their sustenance [11].

In the Ganja-Gazakh region and the low mountainous areas, the climate is characterized by a semi-desert and dry steppe type, with mild winters and hot, dry summers. In the mid-mountainous areas, the climate is moderately warm with dry winters, while in the high mountainous areas, a cold climate with dry winters prevails. The distribution of precipitation increases with elevation up to about 800-1400 meters. Beyond this elevation, the amount of precipitation begins to decrease [10].

Table 2

Results of the long-term trend analysis of precipitation amounts

Stansiya	Trend	Kendall tau	p-value	Sen's slope (mm/il)
Dashkasan	Decreasing	-0.12	0.18	-0.7
Goygol	Decreasing	-0.15	0.1	-1.1
Gadabay	Increasing	0.1	0.22	0.8
Shamkir	No trend	-0.03	0.75	-0.2
Agstafa	Decreasing	-0.18	0.05	-1.4
Ganja	No trend	0.02	0.8	0.1

Air masses arriving from the west contribute to year-round precipitation in the region. During transitional seasons, intense insolation in the lowland and low mountainous areas leads to the development of strong convective processes in the mid- and high mountainous zones. Thus, due to orographic influence, the formation of atmospheric precipitation intensifies from early summer to mid-autumn. Additionally, large-scale mesoscale and synoptic processes further enhance precipitation throughout the year. Typically, at the end of spring and during the early summer and autumn months, convective activity increases across the region, resulting in heavy, short-duration (convective) rainfall [6, 11].

In this study, the non-parametric Mann-Kendall test was applied to the meteorological station time series for 1961-2023 to detect the presence and direction of trends. The trend magnitude was estimated using Sen's slope method. The results are presented in the following table (Table 2).

The results of the Mann-Kendall and Sen's slope analyses presented in Table 2 indicate that, over the study period, the long-term variation of precipitation at the hydrometeorological stations shows a significant decrease at Aghstafa station. At the other stations, the decrease is less pronounced.

Although negative Kendall tau and Sen's slope values at Dashkasan and Goygol stations indicate a declining precipitation trend, the high p-values suggest that these changes are not statistically significant. At Aghstafa station, the decreasing trend is more clearly observed, and the p-value is close to the threshold, indicating a higher probability of precipitation decline in this area. A weak increasing trend is observed at Gədəbəy station, but it is also not statistically significant. Statistical tests demonstrate that significant precipitation decreases are already evident in lowland areas (Aghstafa).

Mathematical and statistical analyses of precipitation in the northeastern part of the Lesser Caucasus region for 1991-2023 indicate that the long-term average precipitation in the region is 451 mm (Table 3). Across individual hydrometeorological stations, this value ranges between 252 mm and 689 mm. In the mid-mountainous zone, precipitation increases and fluctuates between 550-700 mm (547-689 mm). Toward the lowland areas, the long-term average precipitation ranges from 250 to 350 mm (252-329 mm). Of the total annual precipitation in the region, approximately 64 % falls during the warm season, while the remaining 36 % occurs in the cold season.

In the northeastern part of the Small Caucasus region, the amount of atmospheric precipitation is almost evenly distributed within the 1400-1600 m area. The maximum precipitation in the region is observed at higher altitudes (where observational data is available) in this area, with 689 mm recorded in Gadabay. The amount of precipitation continues to increase upwards, reaching 2500 m.

Table 3

Annual distribution of atmospheric precipitation in the northeastern part of the Lesser Caucasus region

Station	Season, mm					Annual percentage, %	
	Winter	Spring	Summer	Autumn	Annual	Warm	Cold
Dashkasan	76	210	183	134	604	65	35
Goygol	63	183	178	123	547	66	34
Gadabay	76	236	231	145	689	68	32
Shamkir	41	97	77	68	282	61	39
Agstafa	48	117	85	80	329	61	39
Ganja	35	87	66	64	252	61	39
Region	**57**	**155**	**137**	**103**	451	65	35

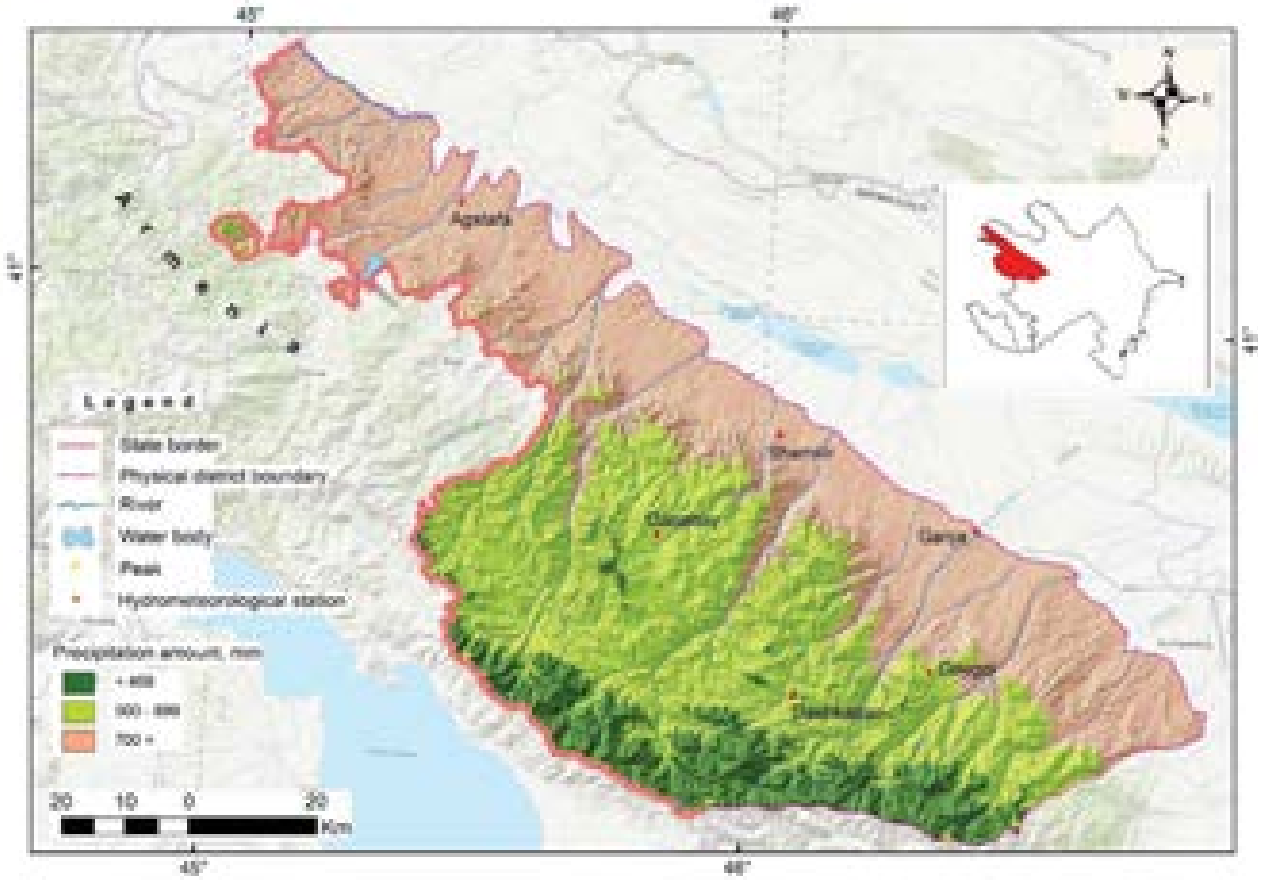


Fig. 1. Average Annual Precipitation Indicators (1991-2023)

However, above 2800 m, in the mountainous area extending to 3600-3700 m, the amount of precipitation decreases again, dropping to around 600 mm [1]. The lowest precipitation in the region occurs in the east, along the boundary with the Kura-Araz lowland, where it falls in the 300-400 m altitude range. Here, the precipitation amount is 252 mm in Ganja.

In the region, the least amount of precipitation is observed in the winter season (57 mm). The wettest season is spring (155 mm). In summer, this value is 137 mm and in autumn, it is around 103 mm. While this distribution holds true for five hydrometeorological stations, there are differences in Goygol. In Goygol, the highest precipitation occurs not in spring, but in summer, with 246 mm recorded

Table 4

Monthly and annual mean precipitation anomalies (mm, %-bold)

Station	Month												Year
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
Dashkasan	-4	-7	-2	-18	-10	-28	-21	-14	-5	-6	-12	-1	-127
	-14	**-21**	**-4**	**-26**	**-10**	**-26**	**-33**	**-32**	**-11**	**-10**	**-30**	**-2**	**-19**
Goygol	0	3	7	-1	-15	-31	-29	-26	-5	2	2	5	-87
	0	**13**	**19**	**-2**	**-15**	**-30**	**-43**	**-48**	**-11**	**4**	**7**	**25**	**-14**
Gadabay	4	6	4	-8	8	-12	-20	-14	-2	1	-6	6	-38
	20	**23**	**10**	**-11**	**7**	**-10**	**-26**	**-28**	**-5**	**2**	**-16**	**29**	**-5**
Shamkir	-2	4	-1	-5	-3	-11	6	-9	-1	-3	-9	0.2	-34
	-18	**24**	**-3**	**-14**	**-8**	**-28**	**31**	**-40**	**-6**	**-9**	**-39**	**2**	**-11**
Agstafa	-3	-4	-5	-11	-12	-18	-1	-17	-9	-6	-14	-6	-104
	-20	**-17**	**-15**	**-28**	**-22**	**-36**	**-2**	**-62**	**-34**	**-15**	**-50**	**-41**	**-28**
Ganja	1	5	-1	-8	-4	-10	-6	-3	-1	-1	-6	0	-33
	11	**37**	**-6**	**-25**	**-9**	**-25**	**-31**	**-17**	**-5**	**-4**	**-32**	**0**	**-12**
Region	-1	1	1	-9	-6	-18	-12	-14	-4	-2	-8	1	-71
	-3	**5**	**2**	**-17**	**-8**	**-24**	**-25**	**-38**	-11	-5	-26	4	-15

A precipitation map has been created to show the spatial distribution of average multi-year precipitation in the northeastern part of the Small Caucasus region (Figure 1). The map was processed using the Digital Elevation Model (DEM) in a GIS environment. The map, processed in 3D format, depicts both the vertical and horizontal distribution of precipitation across the area. The application of hillshade effects on the map allows for clearer differentiation of color gradients representing precipitation distribution. Observing the spatial distribution of precipitation, we can identify a consistent pattern: rainfall amounts increase from the Ganja-Gazakh lowlands toward the high mountain zones.

In the region's low mountain zone (0-500 m), precipitation amounts are minimal. As elevation increases into the mid-mountain zone (up to 1400-1600 m), precipitation shows a marked increase. Although permanent glaciers do not form above the snow line (3000 m) in the study area, persistent snow patches that survive through the following summer are observed in high-altitude zones (Murovdag, Shahdag).

The study statistically assessed the impacts of climate change on long-term precipitation amounts in the northeastern part of the Lesser Caucasus region (Table 4). For this purpose, a comparative analysis was conducted between observed precipitation indices and the climatic norm (1981-2010).

To evaluate the impacts of climate change on precipitation in the region, the average monthly precipitation indices were compared with the climatic norm (1981-2010). In January, precipitation amounts remained unchanged in Goygol, increased in Ganja (11 %) and Gadabay (20 %), while other stations showed decreases of 14-20 %. In February, this indicator decreased in Dashkasan (21 %) and Agstafa (17 %), but increased by 13-37 % at other stations. Compared to the climatic norm, March saw increased precipitation in Goygol (19 %) and Gadabay (10 %), while other stations recorded decreases of 3-15 %. In April, this indicator decreased at all stations, ranging between 2-28 %. In May, while Gadabay showed a 7 % increase, other stations observed precipitation decreases of 8-22 %. During June (10-36 %), August (17-62 %), and September (5-34 %), all stations in the region recorded significant decreases in precipitation compared to the climatic norm. In July, while precipitation in Shamkir increased by 31 % compared to the climatic norm, other stations experienced 2-43 % less rainfall.

In October, precipitation increased by 2-4 % in Goygol and Gadabay, while other stations recorded decreases of 4-15 %. November saw a 7 % increase in Goygol, but other stations experienced reductions ranging from 16-50 %. Compared to the climatic norm, December values decreased in Dashkasan (2 %) and Agstafa (41 %), remained unchanged in Ganja, and showed increases of 2-29 % at other stations.

The annual fluctuations of precipitation in the northeastern part of the Lesser Caucasus region for 2011-2023, compared to the climate norm (1981-2010), are shown in Figure 2. The long-term average precipitation in the region was 415 mm, while the climate norm was 485 mm, representing a decrease of 71 mm or 14 %. Comparing the 2011-2023 precipitation values with 1961-1990, greater changes are observed in the recent period. During 2011-2023, the highest precipitation amounts occurred in July-August, accounting for 30-40 % of the monthly norm. Compared to 1961-1990, the long-term average precipitation for the region in 2011-2023 decreased by 86 mm or 17 %.

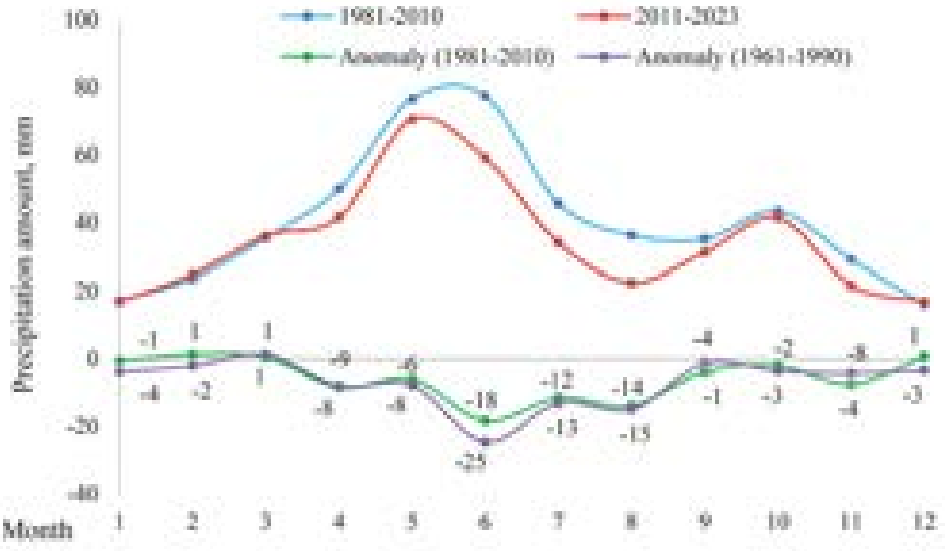


Fig. 2. Variability of mean monthly precipitation amounts in the northeastern Lesser Caucasus region

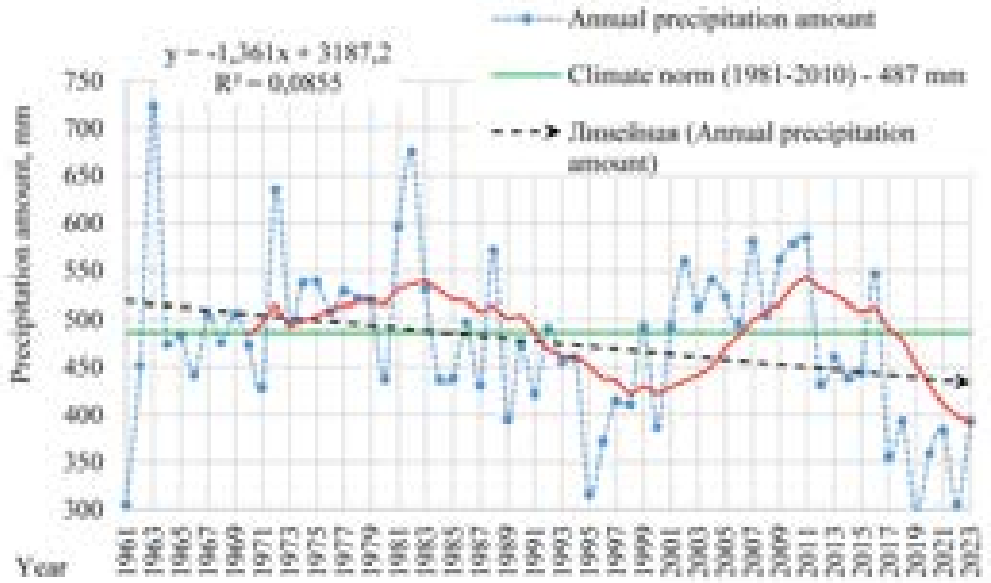


Fig. 3. The multi-year dynamics of precipitation in the northeastern part of the Lesser Caucasus region

The highest annual decrease in precipitation was recorded in Agstafa (28 %), while the lowest was observed in Gadabay (5 %). Looking at the graph, we can see that the most significant reductions occurred from mid-spring to the end of summer. Specifically, in the region, precipitation decreased by 17 % (9 mm) in April, 24 % (18 mm) in June, 25 % (12 mm) in July, 38 % (14 mm) in August, and 26 % (8 mm) in November. Compared to the normal levels, the precipitation amount decreased by 3 % (1 mm) in January, 8 % (6 mm) in April, 11 % (4 mm) in September, and 5 % (2 mm) in November. However, slight increases in this indicator (4-5 %) were recorded in December and February. Although there were reductions in the fall, they were of minor significance. The sharp declines in precipitation during the summer months negatively affect productivity in the agricultural sector. Additionally, due to the impacts of climate change, the intensity of torrential rains and hail events has shifted over time, and their increasing frequency causes severe damage to agricultural areas.

A graph has been constructed to determine the dynamics of annual precipitation indicators over an extended period in the northeastern part of the Lesser Caucasus region (Figure 3). The graph includes the multi-year trend of precipitation, the trend line, the moving average, and the climate norm. Upon examining the graph, we can observe that the precipitation amount in the region fluctuates between 300-750 mm.

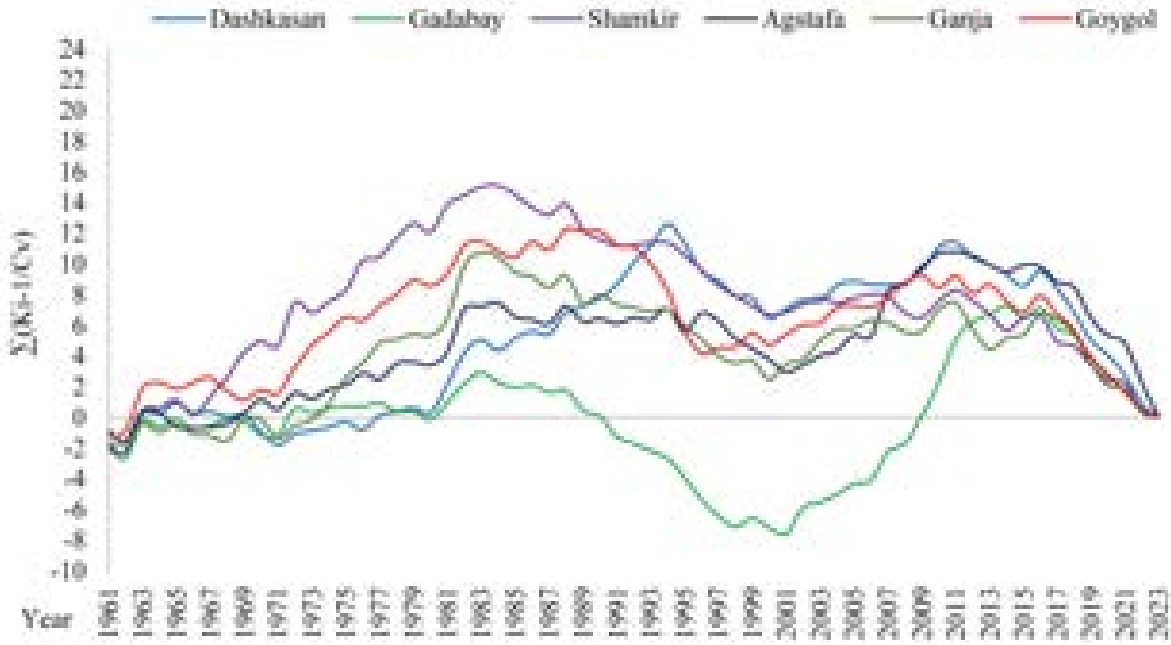


Fig. 4. Dynamics of the precipitation difference integral (1961-2023)

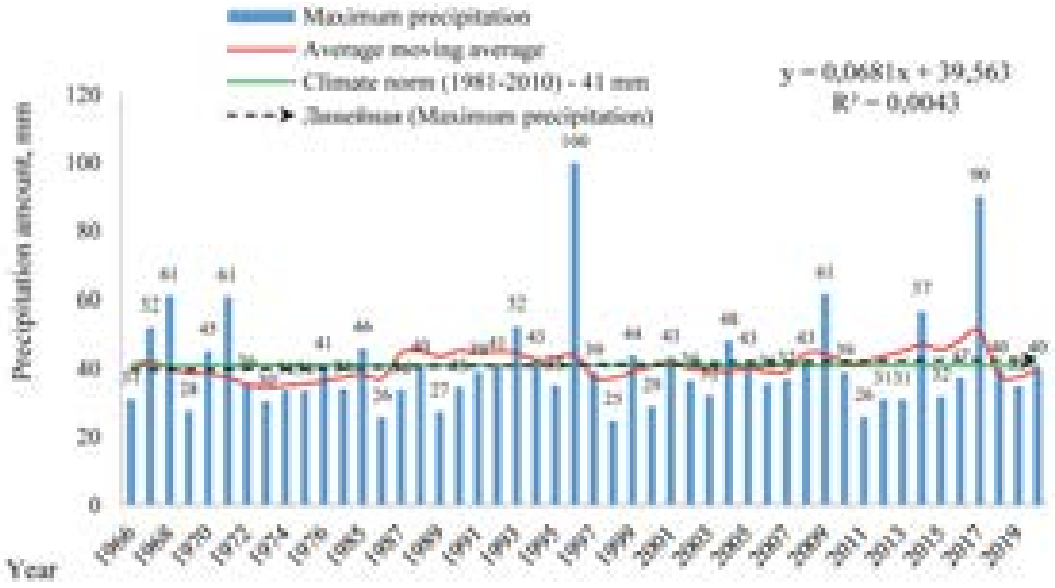


Fig. 5. Annual absolute maximum precipitation in the Northeastern part of the Lesser Caucasus region

Focusing on the dynamics of the moving average, it can be clearly seen that precipitation increased during 1970-1983, 1999, and 2000-2011, and decreased during 1984-1998, 2000, and 2012-2023. In this region, the years 1961, 1995, 1996, 2000, 2017, 2018, 2019, 2020, 2021, and 2022 were among the driest, while 1963, 1972, 1981, 1982, 1988, 2002, 2007, 2009, 2010, and 2011 were among the wettest decades. Analyses also show that all the wettest years occurred before 2011, whereas 90% of the driest years were observed in 1995 and later. The highest average annual precipitation in the region was recorded in 1962 (723 mm), while the lowest was in 2019 (299 mm).

In order to determine the variations of atmospheric precipitation at individual stations in the northeastern part of the Lesser Caucasus region, a differential integral curve has been constructed for each station (Figure 4).

By examining the graph, it becomes evident that the fluctuations of the differential integral curves for the Dashkasan, Shamkir, Aghstafa, Goygol, and Ganja hydrometeorological stations are similar. Specifically, the amount of precipitation increased during the periods 1961-1983 and 2002-2011, while it decreased during 1984-2001 and 2012-2023. The differential integral curve for Gadabay shows some variation. That is, an increase in precipitation was observed during 1961-1994 and 2001-2010, while a decrease occurred during 1994–2000 and 2011-2023. An analysis of the differential integral curves of individual stations in the region shows that all stations exhibit a similar downward trend in precipitation after 2010.

A comparative analysis of the maximum monthly and annual (1961-2020) atmospheric precipitation values in the northeastern part of the Lesser Caucasus region was conducted, comparing them with the norm. The results of the analysis are presented in the description below (Figure 5). Upon examining the analysis, it can be observed that the highest precipitation values were recorded in 1996 (90 mm) and 2017 (100 mm). The graph shows that the linear trend of maximum precipitation has a weak positive tendency. If we focus on the moving average, we observe that the maximum precipitation values were below the norm during 1967-1986, 1997-2000, 2002-2008, and 2018-2020, while they were above the norm during 1966, 1987-1996, 2001 and 2007-2017. The moving average reached its maximum value in 2017.

The analysis of the maximum annual precipitation values in the northeastern part of the Lesser Caucasus region compared to the climatic norm (1981-2010) was conducted for separate 10-year periods. Specifically, an increase of 6 % was observed in 1961-1970, a decrease of 4 % in 1971-1980, a decrease of 16 % in 1981-1990**,** an increase of 9 % in 1991-2000, and an increase of 2 % in both 2001-2010 and 2011-2020.

The study also examined precipitation recurrence patterns across the entire region (Figure 6). The most frequently occurring precipitation events (21 %) were low-intensity rains (< 10 mm). The second most recurrent category (17 %) comprised moderate precipitation events (11-20 mm). Significant recurrence rates were also observed for 21-30 mm (16 %), 31-40 mm (14 %), and heavy precipitation events (> 70 mm, 14 %). The least frequent events (4 %) fell within the 61-70 mm range. The predominance of < 10 mm precipitation indicates a high frequency of dry days, particularly in low-mountain areas. However, this pattern

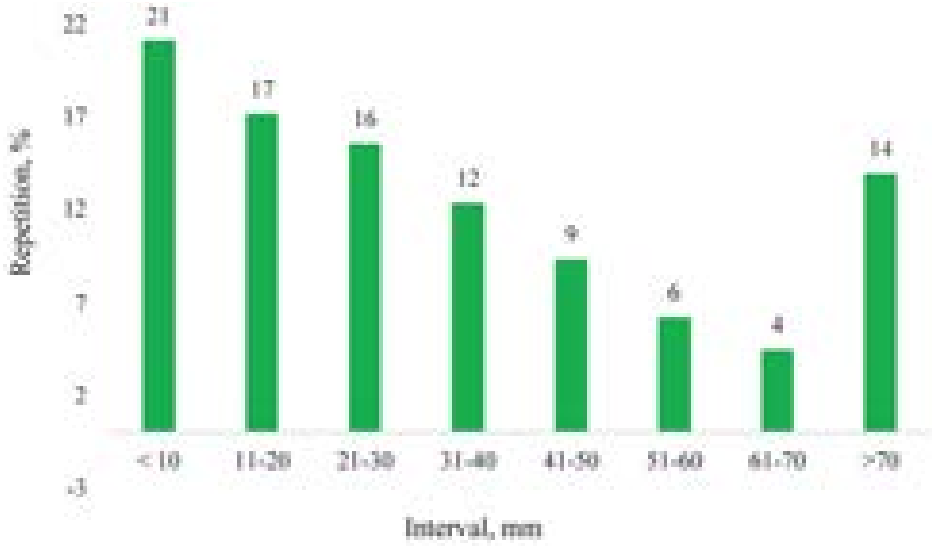


Fig. 6. Recurrence (%) of annual precipitation amounts in the northeastern part of the Lesser Caucasus region

reverses at higher elevations (> mid-mountain zones), where heavy precipitation events (> 70 mm) dominate. Such intense rainfall typically results from convective processes (mainly torrential rains), which frequently trigger flash flood events in the region.

Additionally, in the study, the trend of the precipitation amount in the region from 1961 to 1970 was analyzed, with the tendency of each decadal indicator compared to the previous 10 years (Figure 7).

According to the analysis, compared to the period of 1961-1970, the amount of precipitation increased by 6 % in 1971-1980, by 2 % in 1981-1990, and decreased by 16 % in 1991-2000. Compared to the previous decade, this indicator increased by 27 % in 2001-2010. In the region, precipitation decreased by 19 % in the 2011-2020 decade and by 20 % in 2021-2023.

In the northeastern part of the Lesser Caucasus region, the decade with the highest precipitation over the long-term period was 2001-2010 (535 mm), while the decade with the lowest precipitation was 1991-2000 (422 mm).

Conclusions. Based on observational data for 1961-2023, the study of the spatiotemporal distribution of atmospheric precipitation under climate change in the northeastern part of the Lesser Caucasus region yielded the following results:

1. For the first time, it was determined that 65 % of atmospheric precipitation falls during the warm half of the year and 35 % during the cold half in 1991-2023. In the recent period, the highest monthly precipitation peak was recorded in Gadabay (1100 m).
2. Precipitation in the region increases from 250-300 mm in lowlands to 550–600 mm in high-mountain areas.

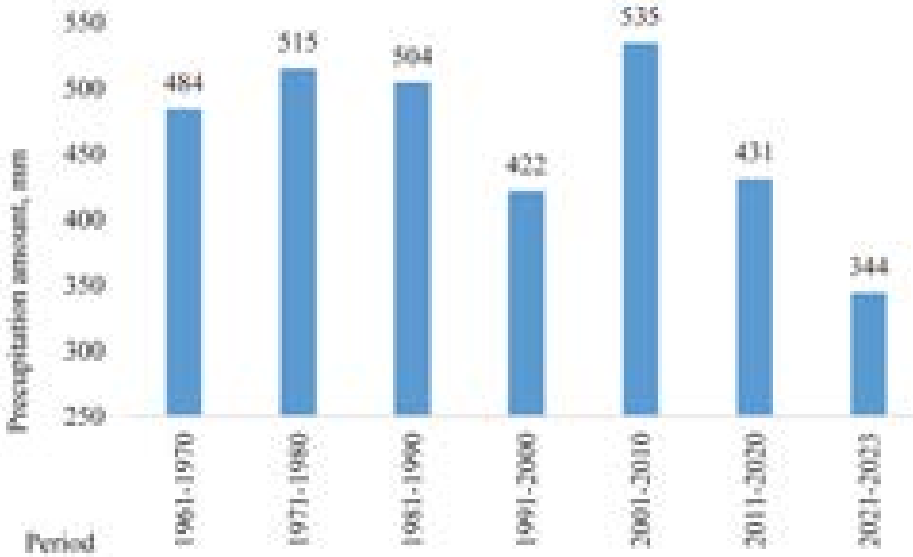


Fig. 7. Dynamics of precipitation amount by decades in the northeastern part of the Lesser Caucasus region

3. In the study area, precipitation during 2011-2023 decreased by 15 % (71 mm) compared to the norm. According to the integral curve, precipitation at all stations in the region has declined since 2015.

4. In the northeastern part of the Lesser Caucasus region, annual maximum precipitation values, compared to the 1981-2010 norm, increased by 6 % in 1961-1970, 9 % in 1991-2000, and 2 % in both 2001-2010 and 2011-2020, while decreases of 4 % and 16 % were recorded in 1971-1980 and 1981-1990, respectively.

The results of the study indicate that atmospheric precipitation in the northeastern part of the Lesser Caucasus region was affected by climate change during 2011–2023. Spatial (from lowlands to high mountains) and temporal (long-term, seasonal, monthly, and quarterly) trends of precipitation suggest that the current state of atmospheric precipitation should be considered in climate zoning and the assessment of water resources. It should also serve as a key criterion for water resource management in new settlements and energy projects.

The decrease in precipitation in the region may lead to the expansion of drought in lower elevations, reduction of green landscapes, and increased frequency of hazardous hydrometeorological events. In agriculture, drought-resistant crops should be cultivated, and modern irrigation technologies (sprinkler and drip systems) should be applied.

The study's findings should be used for the re-evaluation and mapping of climate resources and types, as well as for planning settlements, industrial and economic sectors, and forecasting water resources. Future research is needed to quantify the impacts of rising air temperatures on precipitation and evaporation indicators.

Внесок авторів: всі автори зробили рівний внесок у цю роботу
Конфлікт інтересів: автори повідомляють про відсутність конфлікту інтересів
Декларація про використання генеративного штучного інтелекту: автори підтверджують, що під час підготовки рукопису не використовувалися інструменти штучного інтелекту.

Authors Contribution: All authors have contributed equally to this work
Conflict of Interest: The authors declare no conflict of interest

Declaration of use of generative artificial intelligence: The authors confirm that no AI tools were used during the preparation of the manuscript.

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Характеристика сучасного просторово-часового розподілу атмосферних опадів у північно-східній частині регіону Малого Кавказу

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АНОТАЦІЯ

Метою дослідження є визначення сучасних просторово-часових характеристик розподілу атмосферних опадів у північно-східній частині регіону Малого Кавказу, а також впливу змін клімату на довгострокові кількості опадів, на основі початкових даних про опади за період 1961-2023 років. В аналізі використовувалися дані про опади (місячні, сезонні, річні та багаторічні) з шести гідрометеорологічних станцій, що працювали в цьому регіоні протягом зазначеного періоду. Дослідження проводилося з використанням математико-статистичних, картографічних та фізичних методів. Для визначення просторової картини розподілу було нанесено на карту зміну річної кількості опадів з висотою за допомогою ГІС-технологій. Результати дослідження показують, що 65% річних опадів випадає в теплий період, тоді як 35% – у холодний період року. У регіоні кількість опадів збільшується від низовин до високих гір. Кількість опадів, яка піднімається до верхньої межі середньогірської зони, має тенденцію до зменшення вище приблизно 2800 м. Період, коли кількість опадів у регіоні найбільше зменшується, відповідає червню-вересні, протягом якого потреба в питній воді досягає свого максимального рівня. У багаторічному періоді 90% 10 років з меншою кількістю опадів припадали на період після 1995 року. Однак протягом цього періоду було зафіксовано збільшення екстремальних кількостей опадів. Це підтверджує, що більша частина річних опадів випадала під час таких подій, тоді як посушливі умови посилювалися в інші фази року. Багаторічна середня кількість атмосферних опадів у північно-східній частині регіону Малого Кавказу (1991-2023) становила 451 мм, що на 15% (71 мм) нижче за норму (1981-2010). Максимальна кількість опадів зареєстрована переважно в Гедабаї (до 1000 мм). Найбільш вологий період у регіоні припав на 2001-2010 роки, а найсухіший – після 2010 року. Різке зменшення кількості опадів влітку суттєво впливає на вирощування сільськогосподарських культур та садівництво в низовинах, а також на сінокосаріння та тваринництво в гірських районах. Рекомендується висаджувати посухостійкі культури та використовувати сучасні технології зрошення (дощувальні та крапельні системи) у сільському господарстві. Визначення сучасного просторово-часового розподілу опадів у цьому регіоні має важливе значення для пом'якшення наслідків зміни клімату, розробки стратегій адаптації та оцінки альтернативних джерел енергії.

ІНФОРМАЦІЯ ПРО СТАТТЮ :

Рукопис надійшов
15 грудня 2025

Отримано після рецензування
29 квітня 2026

Затверджено до друку
25 травня 2026

Опубліковано онлайн
30 травня 2026

Ключові слова:

глобальне потепління, кількість опадів, багаторічна мінливість, щомісячний максимум опадів, середня ковзна кількість, ГІС-технологія, періодична кількість опадів, інтеграл різниці, регіон Малого Кавказу.

https://doi.org/10.26565/2410-7360-2026-64-14

UDC 502.13:528.8.04(477.62)

Belligerent transformation of protected ecosystems of the Dvorichansky National Nature Park and its surroundings according to remote sensing data

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ABSTRACT

Purpose of the study. Full-scale military aggression in eastern Ukraine has caused unprecedented pressure on protected ecosystems, which requires an objective assessment of damage to develop restoration strategies. The purpose of the study is to assess the belligerent transformation of protected ecosystems in the Dvorichansky National Nature Park and its adjacent territories using remote sensing data and to provide a comprehensive assessment of their transformation in the period 2021–2025. The work aims to identify the spatiotemporal dynamics of vegetation activity, analyse the destabilisation of unique Cretaceous outcrops, and mathematically confirm the statistical significance of the transformation of natural complexes under the influence of military factors.
The study contributes to the implementation of UN Sustainable Development Goals 13 and 15, providing a scientific basis for ecosystem restoration strategies.
Materials and methods of research. Military aggression in eastern Ukraine has severely impacted protected ecosystems, necessitating an objective damage assessment for restoration planning. This study evaluates the belligerent transformation of the Dvorichansky National Nature Park and adjacent territories from 2021 to 2025 using remote sensing. Our work identifies spatiotemporal vegetation dynamics, analyses Cretaceous outcrop destabilisation, and statistically confirms ecosystem transformation due to military factors.
Results. Analysis of Sentinel-2 satellite data for 2021–2025 revealed the transformation of 46.5% of the studied area (the Dvorichansky National Park and its surroundings).

ARTICLE INFO

Manuscript received
15 February 2026

Revised manuscript received
27 April 2026

Manuscript accepted
25 May 2026

Available online
30 May 2026

In cites: Krainiuk Olena, Buts Yuriy, Katkovnikova Lidiia, Sukhov Valeriy, Lisnyak Anatoliy, Zolochevskyi Denys (2026). Belligerent transformation of protected ecosystems of the Dvorichansky National Nature Park and its surroundings according to remote sensing data. *Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology*, (64), 176–191. https://doi.org/10.26565/2410-7360-2026-64-14



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The greatest damage was recorded in built-up areas (62%) and forest areas (45%) located in the adjacent territories. In forests, the share of severe damage increased to 16% due to delayed tree death. A "pseudo-recovery" effect was observed in abandoned fields: in 2022–2024, the NDVI index increased artificially due to mass ruderalization (weed infestation), but in 2025 the vegetation rate fell by 18% below the pre-war level, indicating soil depletion. On chalk slopes, bare rock area increased by 38% (from 42 to 58 hectares). Explosions and turf rupture reduced the integrity index from 0.85 to 0.62, triggering active erosion and ravine formation. Statistical testing (paired t-test, $p < 0.05$) confirms these changes result from military impact rather than natural fluctuations. Our transformation model illustrates how primary damage triggers cascading, irreversible erosion and chemical degradation.

Keywords:

remote sensing, NDVI index, soil erosion, military impact, turf integrity index, landscape transformation, vegetation degradation, UN Sustainable Development Goals.

Introduction. Statement of the general problem

Full-scale military aggression against Ukraine has caused unprecedented pressure on the environment, the consequences of which can no longer be considered only as a local problem. As of 2026, the belligerent transformation of ecosystems has become systemic, requiring a review of approaches to monitoring and restoring ecosystems. Belligerent transformation includes the transformation of the natural landscape as a result of military actions or other military-related activities, including its complete loss due to cutting down, burning, moving military equipment, deploying military units, destroying or blocking ecological corridors, etc. [1, 2].

The Kharkiv region, as a border and strategically important zone, has experienced one of the most significant impacts: from direct landscape destruction to long-term chemical pollution of soils and waters. Of particular concern is the state of the objects of the nature reserve fund, particularly the Dvorichansky National Nature Park, which is a centre for unique Cretaceous ecosystems. The connection of this problem with practical tasks lies in the need to develop digital tools for recording ecocide for international courts and planning post-war restoration.

The study's relevance stems from the long-term presence of protected areas in the combat zone, which makes traditional field research impossible. In such conditions, remote sensing of the earth becomes almost the only method for assessing the dynamics of damage to biodiversity and vegetation cover.

Analysis of recent research and publications. Over the past five years, the impact of war on the environment has become a key issue in the works of both Ukrainian and foreign scientists. The destruction of entire ecosystems, significant pollution of soil, water, and air, and the rapid decline in biodiversity are challenges that require not only mitigation but also the development of effective restoration strategies. The general environmental impact of war and the degradation of the protected area fund were studied in detail by Tsaryk and Kuzyk [3]. Antonenko and Khutkyi [4] focused on how aggression destroys the country's natural resources and tourism potential. The economic side of environmental damage and the administrative levers for the rehabilitation of territories were analysed in the works of Tytykalo [5] and Blagopoluchna [6].

A separate body of research is devoted to the «invisible» consequences of explosions – atmospheric pollution and the accumulation of heavy metals in soils. These aspects are discussed in detail in the publications of Matkivskyi [7], Krainiuk [8] and Shebanina [9]. The specifics of soil cover destruction in the Kharkiv region were studied by Kurach [10] and others, and the legal qualification of the aggressor's actions as ecocide is substantiated in the works [12, 13].

Studies of the environmental aspect of the war show horrific statistics: since 2014, the Russian Federation has illegally seized or destroyed more than 500 objects of the natural reserve fund of Ukraine, covering an area of over 1.2 million hectares [3]. Dozens of national parks, reserves, botanical gardens and zoos have been occupied [4]. The authors [5] indicate that, as of 2022, about 20% of the country's protected areas had been damaged by Russian aggression. This includes 4 biosphere reserves and 17 wetlands of international importance, totalling over 627 thousand hectares. In addition to the direct destruction of flora and fauna, this entails enormous financial losses. The economic and environmental losses exceeded 200 billion hryvnias in 2022, and this figure continues to grow rapidly, along with the area of degraded land and the loss of unique species [6].

The scale of the problem forces researchers to look for new methods of damage assessment, as the current hostilities in Ukraine have a catastrophic impact on all components of the natural environment. Environmental impacts can be effectively assessed using satellite monitoring and the NDVI index. Analysis of Sentinel-2 satellite images showed a 48% decrease in NDVI in 2022 compared to 2021 in the Kupyansk and Izyum areas, indicating large-scale destruction of vegetation cover due to hostilities, fires, and the movement of heavy equipment [14]. Soil studies revealed increased levels of heavy metals (Cd, Cu, Pb) in the shelling areas, as well as physical

disturbances to the soil cover caused by explosions and the movement of military equipment [15, 16]. Satellite monitoring also allows for tracking atmospheric pollution, water resources, and landscape changes, which is critically important for planning ecological rehabilitation measures [8, 17, 18, 19]. A significant problem is the degradation of protected areas and national parks [20]. In general, satellite data and the NDVI index are key tools for the operational monitoring of the environmental consequences of war [21].

Military operations in the Kharkiv region are causing large-scale ecological destruction, leading to the loss of biodiversity and the destruction of natural habitats in nature reserves and ecoparks, particularly in Feldman Ecopark [19]. In addition to the direct destruction of species, there is a systematic contamination of soil, water [8] and air with heavy metals and petroleum products [2, 8, 9, 10]. This not only reduces land fertility but also creates long-term threats to human and animal health. A separate factor in transformation is the destruction of infrastructure, which negatively affects water resources and fisheries in the region [21], resulting in significant losses in aquaculture and commercial fishing.

The transformation of forest landscapes through fires, explosions and the construction of fortifications worsens the condition of the soil cover and changes the natural relief [14, 21]. The greatest destruction of agricultural lands is caused by air and artillery strikes, which lead to food contamination and crop losses. The scale of damage in the region is critical: more than 20 thousand affected objects have been recorded, a third of which falls on the city of Kharkiv [11]. The combination of these factors, including the destruction of industrial facilities and long-term environmental pollution, provides grounds for qualifying the aggressor's actions as environmental crimes and ecocide [12, 13]. Overcoming these irreparable consequences requires increased legal responsibility and attracting international support for the future restoration of ecosystems [11, 18].

Highlighting previously unresolved parts of the overall problem. Despite significant current work describing the overall ecological damage, many questions remain unanswered, especially in the context of a protracted military conflict. As hostilities continue for the fifth year, we are witnessing a transition from acute impacts to chronic ecosystem degradation. Most of the existing studies were based on data from the first two years of a full-scale invasion. However, as of 2026, there is an urgent need to assess the cumulative effect - the cumulative damage from continuous shelling, mining and fires affecting the same territories over a long period of time.

A separate unresolved problem is the state of highly specialised ecosystems, such as the unique Cretaceous deposits of the Dvorichansky National Park. These landscapes have a low ability to regenerate, and any mechanical destruction or chemical pollution here can become irreversible. The mechanism of natural self-recovery in areas where human activity has completely ceased due to danger remains insufficiently studied. Whether ecosystems can autonomously recover from warfare-induced damage or if territorial neglect exacerbates environmental transformation remains a critical question requiring rigorous analysis through advanced GIS technologies.

In addition, a critically important task is the systematic documentation of environmental crimes in the Russian Federation. Each case of forest destruction or water pollution should be recorded not just as a statistical fact, but as legally significant evidence of ecocide. In this article, we try to fill the gap in the methodology of remote monitoring, which allows not only to assess the area of damage, but also to predict the viability of protected areas in the post-war period, which is the foundation for future lawsuits in international courts and the development of environmental rehabilitation programs.

The purpose and objectives of the research. The purpose of the article is to study the belligerent transformation of protected ecosystems in the Dvorichansky National Nature Park using remote sensing data and to comprehensively assess their degradation over the period 2021–2025.

The following tasks were to be solved:

1) A comprehensive analysis of the impact of prolonged military operations on the ecosystems of the Kharkiv region (in particular, the Dvorichansky National Park) and the justification of strategies for their restoration in the context of sustainable development of the region.

2) To achieve this, it is planned to assess the scale of transformation of natural landscapes using modern remote sensing methods,

3) Investigate the dynamics of soil and water pollution, as well as formulate practical recommendations for the rehabilitation of damaged areas, drawing on international experience and public initiatives.

The research methodology is based on a combination of remote sensing, geospatial modelling, and mathematical statistics. The primary data source is Sentinel-2 multispectral imagery accessed via the Copernicus Browser. These data were selected because of their high spatial resolution (10 m), which is critical for monitoring protected areas in regions of active military operations.

For the calculation of spectral indices and subsequent comparative analysis, Level-2A (L2A)

products were used. The selection of the L2A product is essential for ensuring the scientific validity of the results, as these data undergo automated atmospheric correction. By converting Top-Of-Atmosphere (TOA) reflectance to Bottom-Of-Atmosphere (BOA) reflectance using the Sen2Cor algorithm, the process ensures a correct quantitative comparison of index image time series. This approach eliminates the influence of atmospheric aerosols and water vapour, meeting the required standards for professional analysis of vegetation dynamics.

Calculation of the NDVI vegetation index enables an objective assessment of vegetation cover and the identification of areas of degradation. The Python programming language was used to automate the processing of large datasets, enabling not only the construction of long-term time series but also the generation of accurate heat maps of landscape changes.

To ensure the scientific validity and reproducibility of the results, the data processing was conducted according to a structured analytical pipeline. The sequence of stages - from automated satellite data acquisition to statistical validation of the identified landscape changes - is detailed in the methodological workflow (Fig. 1).

Object and data. The study is focused on the territory of the Dvorichansky National Nature Park. The primary source of information was satellite images from the Copernicus Browser (Sentinel-2 mission), specifically the Level-2A (L2A) processing level. This data level provides Bottom-Of-Atmosphere (BOA) reflectance, which is mandatory for the professional monitoring of spectral indices like NDVI and ensures the reliability of the calculated values across the 2021–2025 study period.

To ensure maximum analytical precision, time series of satellite data were compiled for the 2021–2025 period. The image selection process was strictly filtered to minimise cloud interference; only scenes with a total cloud cover of less than 20% were utilised for the study. This criterion minimised spectral distortions and ensured data consistency for the accurate comparison of monthly mean NDVI values across the vegetation seasons.

The analysis algorithm included the following steps:

1. Calculation of the vegetation index. The normalised difference vegetation index (NDVI) was used, which allows for an objective assessment of chlorophyll content in plants based

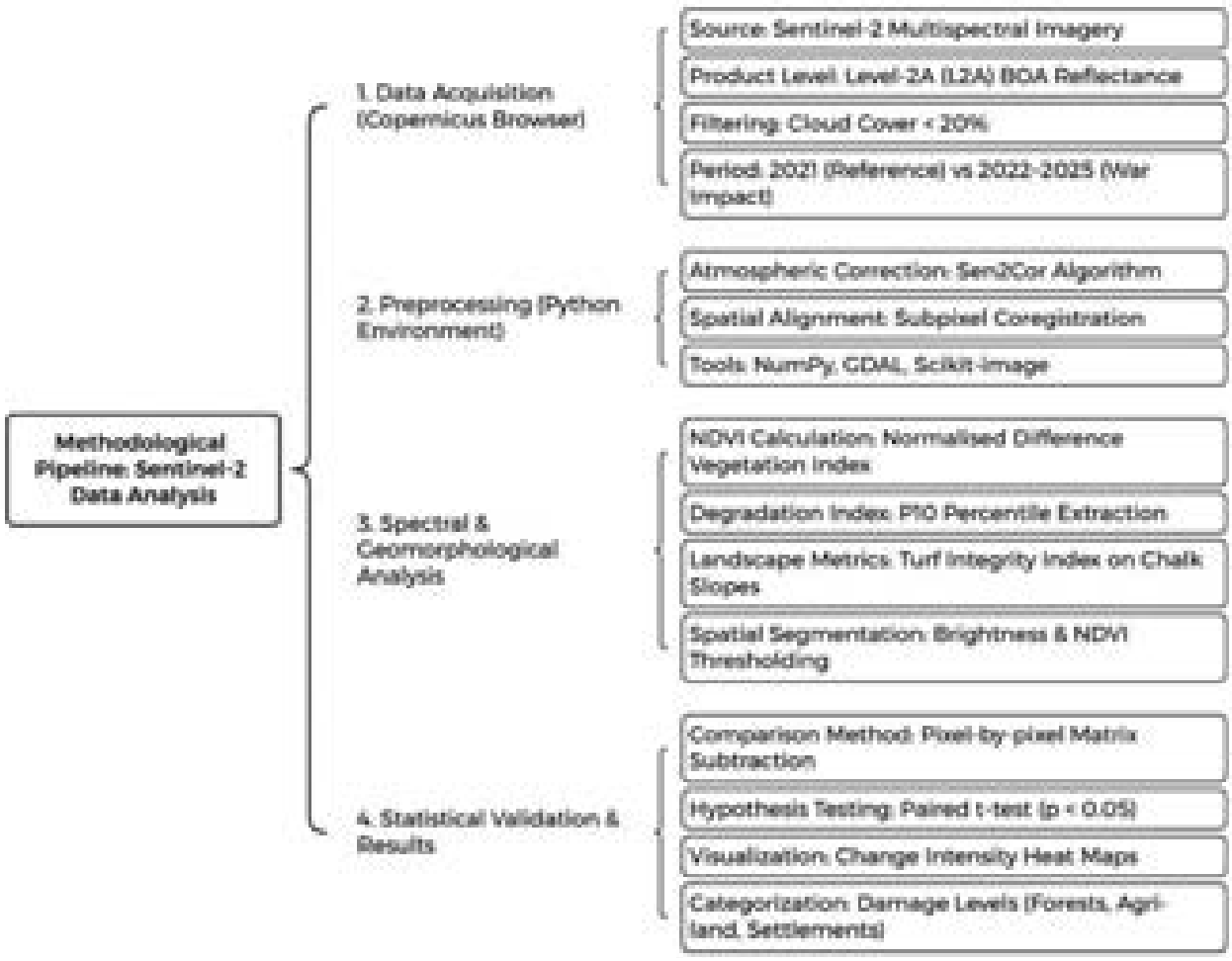


Fig. 1. Methodological framework for Sentinel-2 data processing and analysis

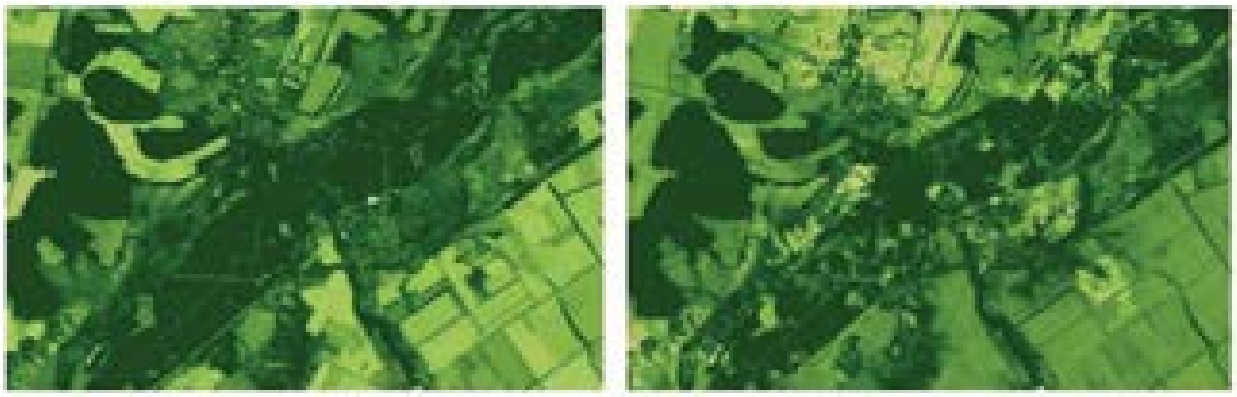


Fig. 2. Satellite images of part of the territory of the Dvorichansky National Park for 10.09.2021 and 07.09.2025

on the difference in reflectance between the red and near-infrared spectra.

2. Time series and comparisons. A comparative analysis of the state of the ecosystem "before" (2021) and "after" (2022–2025) the start of full-scale military operations was conducted.

3. Software processing of the obtained data and comparison of pixel value matrices were carried out in Python using specialised libraries: NumPy (matrix operations), Matplotlib (visualisation), scikit-image (image processing), and GDAL (geospatial data). Statistical analysis included constructing histograms of NDVI values and calculating the areas of damaged areas by category: forests, agricultural lands, and settlements.

This approach ensures high monitoring reliability in conditions where direct access to the territory is limited due to occupation or mine danger.

The impact of military operations on the ecosystem of the Dvorichansky National Park: analysis of vegetation cover changes and prospects for restoration. After previous studies of the ecological state of the Zmiiv and Kupyansky districts [13], we focused on the Dvorichansky National Nature Park. This object is key to understanding the transformation of specific landscapes of the Kharkiv region. Created in 2009, the park covers 3,131 hectares and is a unique centre of steppe ecosystems and chalk deposits that have formed over millions of years. The specific geological conditions of the chalk slopes and the water balance maintained by the Oskil River have created an environment that supports many narrowly endemic species of flora and fauna listed in the Red Book of Ukraine.

However, with the beginning of the full-scale invasion in 2022, Dvorichansky, along with the Slobozhansky and Gomilshanski forest parks, found itself in the zone of active hostilities. This led to uncontrolled landscape transformation, mining of territories, and the destruction of rare habitats. Assessing the damage to such protected areas is a complex scientific challenge that requires modern methods for remotely recording environmental crimes.

Within the framework of this study, the dynamics of the NDVI index for the period 2020–2025 were analysed, enabling us to assess vegetation conditions before and during the military conflict quantitatively. Based on the satellite data obtained, the main factors driving changes in vegetation cover and soils were identified, and the scale of losses to the natural environment was determined. Figure 2 and histograms (Figure 3) show the dynamics of changes in NDVI for the National Nature Park «Dvorichansky» in the Kharkiv region for 2021-2025.

The results presented in Figure 2 allow us to identify changes in the biotic component of the landscape under the influence of the military factor.

A stable distribution with a dominance of high-index values characterised the pre-war state (10.09.2021). The main peak in the range of 0.85 -0.91 indicated the presence of dense, healthy vegetation cover and the absence of significant degradation processes.

The initial phase of degradation (10.09.2022) was marked by a noticeable «blurring» of the right-sided peak and the appearance of additional modalities in the low-value zone (0.1-0.3). Although the maximum values remained high (0.78), the oscillation amplitude became less stable. This indicates the emergence of primary foci of vegetation destruction due to mechanical damage and fires, as confirmed by the expansion of the value range toward the lower end.

The progressive transformation (2023 – 2024) demonstrates a clear trend towards bimodality in the distribution. A significant decrease in the "summer plateau" of vegetation is recorded. In 2023,

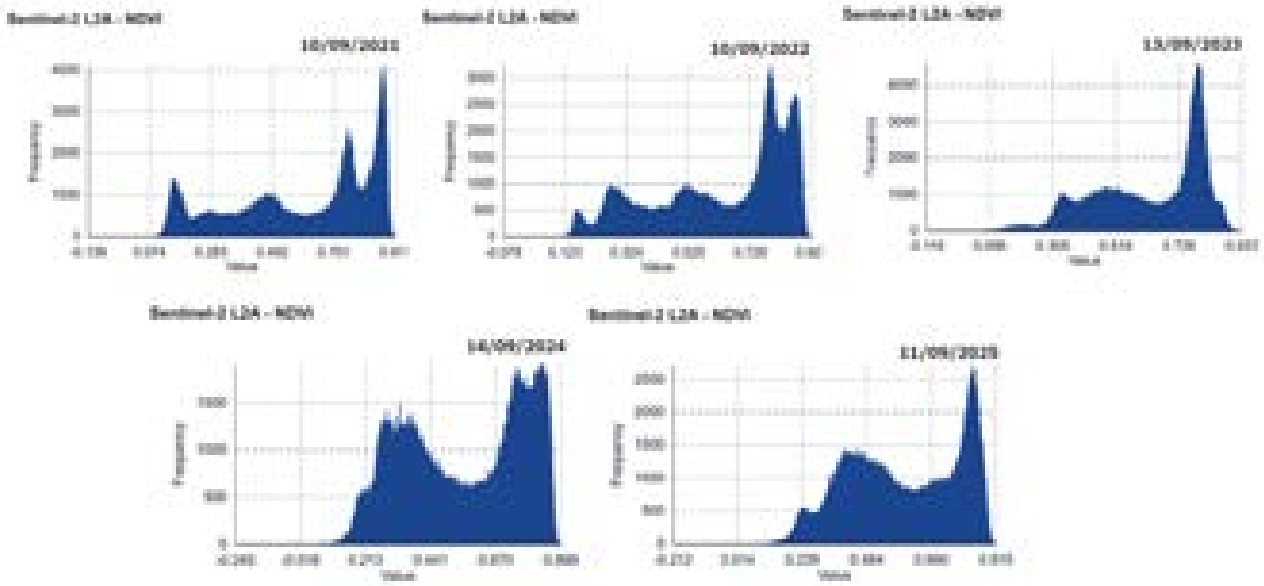


Fig. 3. Histograms of the frequency distribution of the vegetation index NDVI in the territory of the Dvorichansky National Park according to Sentinel-2 data (2021–2025)

the average value in July-August was lower than in the pre-war period. In September 2024 the average NDVI was only 0.595, which is one of the lowest values for this month for the entire observation period (Fig. 4). In 2024, the formation of a stable cluster within 0.2 – 0.4 is observed, which indicates a deep fragmentation of the ecosystem and the transition of a significant part of the protected areas to a state of stable degradation.

The status as of September 11, 2025, records the consolidation of the bimodal structure. Although a certain tract with a high level of vegetation has been preserved, a significant shift of the histogram's "centre of mass" to the left compared to 2021 indicates a cumulative decrease in the park's overall bioproductivity.

The pixel distribution mathematically confirms the systemic degradation of vegetation in the Dvorichansk region, not just local losses. The shift in frequencies towards low NDVI values reflects the true scale of damage, underscoring the need for differentiated restoration strategies for each affected area.

The transformation of the park's vegetation cover is due to a combination of direct and indirect factors of military influence, leading to the systemic degradation of protected landscapes.

The direct impact is manifested in the physical destruction of the vegetation layer from fires, the detonation of ammunition, and mechanical damage from the movement of heavy machinery. Particularly critical for the chalk slopes of the Dvorichansk region is the violation of the integrity of the soil cover, which provokes erosion processes and environmental pollution with heavy metals and explosive residues.

The indirect impact is cumulative and associated with violations of the territory's

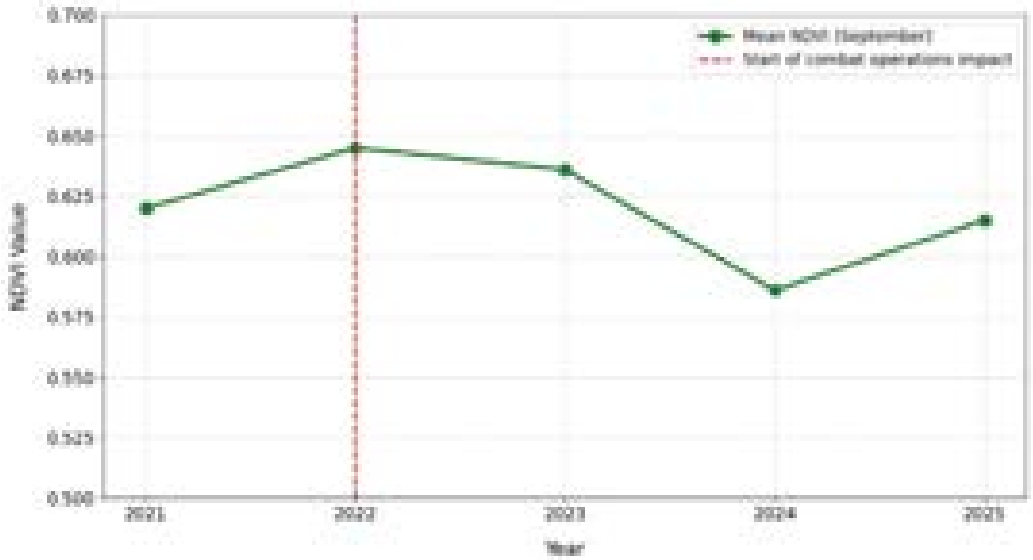


Fig. 4. Dynamics of average NDVI for 2020-2024 (Sentinel-2)

protection and management regimes. The disturbance factor (noise pollution), limited access for scientists to conduct monitoring, and the inability to implement fire prevention measures due to the mine danger create conditions for uncontrolled transformation of ecosystems.

The statistically significant shift in the NDVI index to lower values (0.1-0.5) mathematically confirms the deep degradation of the park's ecosystem after 2022. This indicates that even outwardly «green» areas are losing their biological productivity and resilience, entering a state of chronic ecological stress.

For a more detailed understanding of the depth of the transformation of the ecosystem of the Dvorichansky National Park, a comparative analysis of the average monthly values of the NDVI index for five years (2021–2025) was conducted, which is shown in Fig. 5. This approach allows us to eliminate random daily fluctuations in spectral characteristics and identify stable trends in the transformation or restoration of vegetation cover.

Analysis of the obtained curves indicates a significant deformation of the "green profile" of the territory after the start of full-scale military operations. If in 2021 (the reference period) the graph showed a classic dome-shaped shape with a maximum plateau in June -August (NDVI mean ≈ 0.72 - 0.76), then in subsequent years there is a systematic decrease in the amplitude of these peaks.

The dynamics of 2024 deserve special attention, as the red line on the graph throughout the active season (May-October) was consistently lower than the indicators in all previous years. This mathematically confirms the hypothesis of the cumulative nature of environmental damage: the ecosystem that suffered fires and mechanical damage in 2022–2023 demonstrated the lowest ability to increase phytomass in 2024.

The indicators for 2025 indicate some stabilisation of the state, but the level of vegetation still does not reach pre-war values. The shift in the vegetation peak and the general «sag» of the curve in the summer months indicate a likely change in the species composition of vegetation in damaged areas, where perennial protected communities are replaced by less productive ruderal flora. Thus, the data presented in Figure 5 provide direct evidence that the military impact led to a long-term decline in the viability of the unique ecosystems of the Dvorichansk region.

A comparison of the indicators of the reference year 2021 and 2024, as the period with the greatest cumulative effect of damage, revealed a significant «sag» of the vegetation curve (Fig. 6). In contrast to the pre-war stability, in 2024 a statistically significant deficit of photosynthetic activity was recorded with the largest gap in July and September, which directly correlates with intense fires and mechanical soil destruction.

The decrease in average NDVI resulted from a combination of direct suppression of chlorophyll activity in 39.3% of the park area, chemical contamination of soils by detonation products, and the replacement of perennial protected communities with less productive ruderal flora. Such changes in vegetation structure are observed even in visually intact areas, confirming the systemic nature of the ecosystem transformation.

Thus, the comparison of the "best" and "worst" ecosystem states in Figure 6 confirms that the consequences of military operations are long-

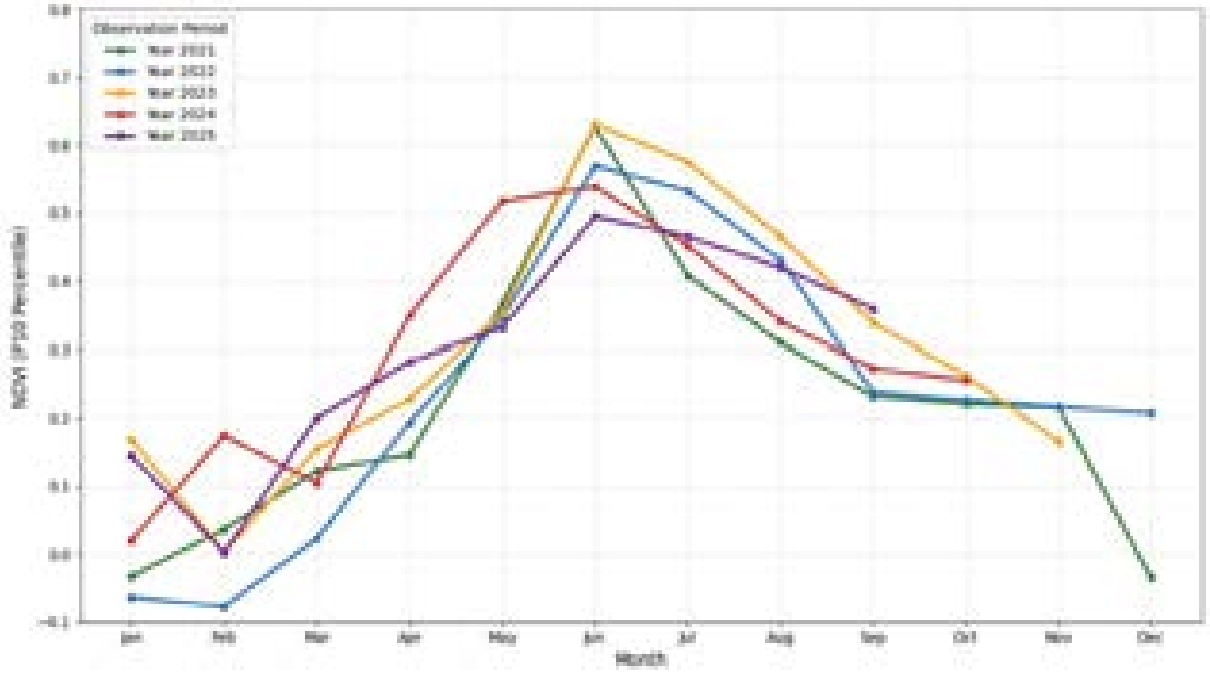


Fig. 5. Comparative seasonal dynamics of average monthly NDVI values of the Dvorichansky National Park (2021–2025) based on the results of processing Sentinel-2 images

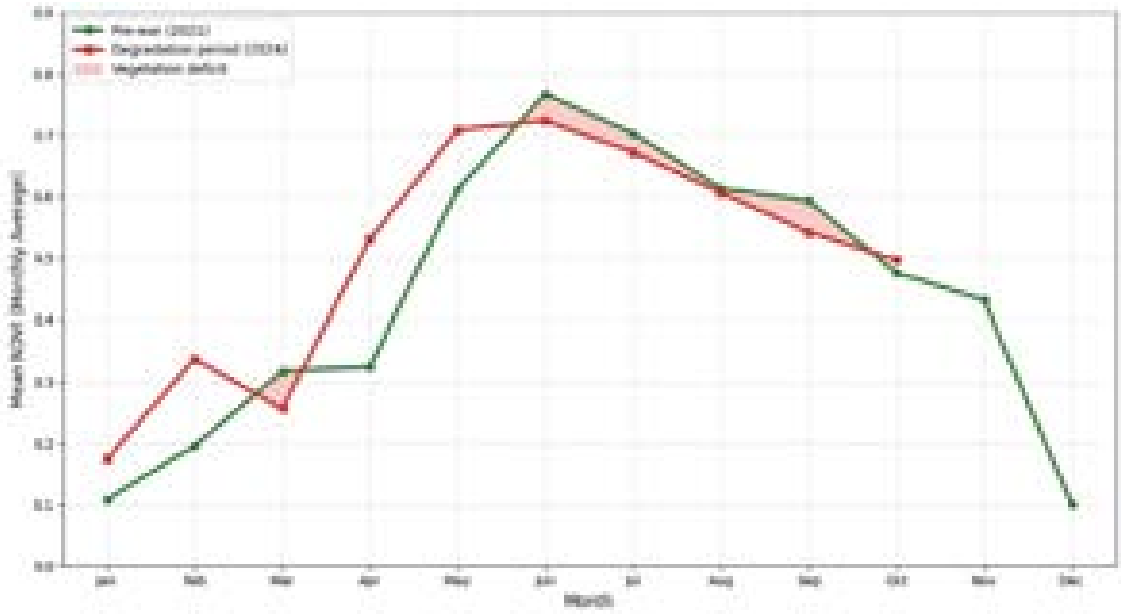


Fig. 6. Comparative analysis of the state of vegetation of the Dvorichansky National Park: reference state before the war (2021) and peak of degradation (2024)

term. Even if the active phase of hostilities ceases, the protected area will require a long period of reclamation and monitoring to return to the baseline vegetation indicators of 2021.

To obtain a clear visualisation of spatial changes and an objective assessment of landscape transformation, an automated comparison of satellite images was conducted for September 10, 2021 and September 11, 2025. The analysis methodology was based on the developed algorithm for pixel-by-pixel comparison of value matrices, followed by the generation of a heat map (Fig. 7).

The processing process included preliminary preparation of Sentinel-2 images in GeoTIFF format with value normalisation and geometric correction for subpixel contour matching. By calculating the difference between image matrices and applying threshold noise filtering, a change mask was created. The final visualisation was implemented by constructing an intensity map, with a gradient from green to red indicating the degree of loss of vegetation capacity. The final statistical stage allowed calculating the areas of degraded areas based on the number of changed pixels, classified by landscape types: forests, chalk slopes, and floodplain meadows.

The automated comparison of satellite data produced a heat map of changes in vegetation cover, showing the dynamics of bioproductivity from September 2021 to September 2025. The map's colour scale is constructed so that blue and dark shades reflect relative stability, while light and bright yellow areas mark significant degradation. The spatial distribution of damage allows us to identify critical areas in floodplain ecosystems and forests, where the mosaic of light spots corresponds to local fires and mechanical

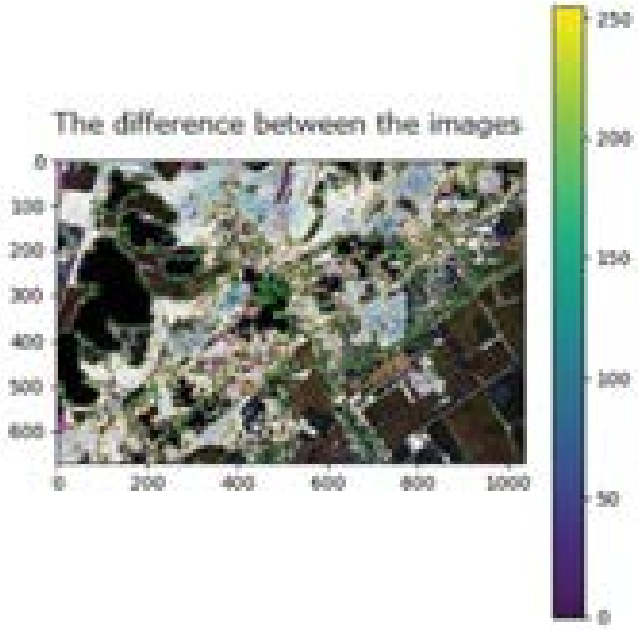


Fig. 7. Results of digital comparison of satellite images of the Dvorichansky National Park for September 10, 2021 and September 11, 2025.

destruction of the tree layer. Particular attention is drawn to chalk slopes, where light contours along steep slopes indicate the expansion of areas of bare substrate and the activation of erosion processes in places of turf disturbance.

The applied algorithm of pixel-by-pixel matrix comparison enabled differentiation between the states of natural ecosystems, residential areas, and agricultural lands. The analysis revealed the heterogeneity of military impact, with both

Table 1

Dynamics of damage to the territories of the Dvorichansky National Park and its surroundings (2024–2025)

Site category	Total area	Degree of damage compared to 2021 (as of 2024)	Degree of damage (as of 2025)
Forests	320 hectares	Damaged: 144 hectares (45%)	Damaged: 141 hectares (44%)
		Strong: 48 hectares (15%)	Strong: 51 hectares (16%)
		No change: 176 hectares (55%)	No change: 179 hectares (56%)
Agricultural land	480 hectares	Damaged: 168 hectares (35%)	Damaged: 178 hectares (37%)
		Strong: 48 hectares (10%)	Strong: 53 hectares (11%)
		No change: 312 hectares (65%)	No change: 302 hectares (63%)
Settlements	150 hectares	Damaged: 90 hectares (60%)	Damaged: 93 hectares (62%)
		Strong: 45 hectares (30%)	Strong: 48 hectares (32%)
		No change: 60 hectares (40%)	No change: 57 hectares (38%)
TOTAL (in the picture)	1080	Average % change: 45%	Average % change: 46.5%

zones of complete transformation and regions of relative stability. An interesting feature is the presence of dark zones of local NDVI growth, which is often due not to ecosystem restoration, but to the cessation of anthropogenic pressure. The absence of agricultural activity led to the spontaneous development of fast-growing ruderal species, which create an optical illusion of improved vegetation. At the same time, light blue areas clearly localise the most intense hostilities, where the combination of mechanical damage, chemical pollution and fires led to the systematic destruction of biogeocenoses. The calculated area of damaged territories is 39.3% of the total area of the studied zone, which confirms the scale of landscape transformation. The detailed statistical results of this distribution are systematised in Table 1 and graphically displayed in Figure 8. It should be noted that for a comprehensive spatial analysis, the region of interest included not only the core of the national park but also adjacent landscapes. Specifically, the large forest tracts, agricultural lands, and settlements analysed for damage are located in the immediate surroundings of the park.

Discussion of the dynamics of transformation and restoration processes

Analysis of the calculated areas of damage in comparison with the reference pre-war period allows us to state a deep systemic transformation of the landscapes of the national park. Compared with the baseline indicators of vegetation in 2021, as of September 2025, the total area of anthropogenically modified territories in the study area increased to 46.5%. This indicates that almost half of the territory has transitioned to a state of persistent ecological stress. Of particular

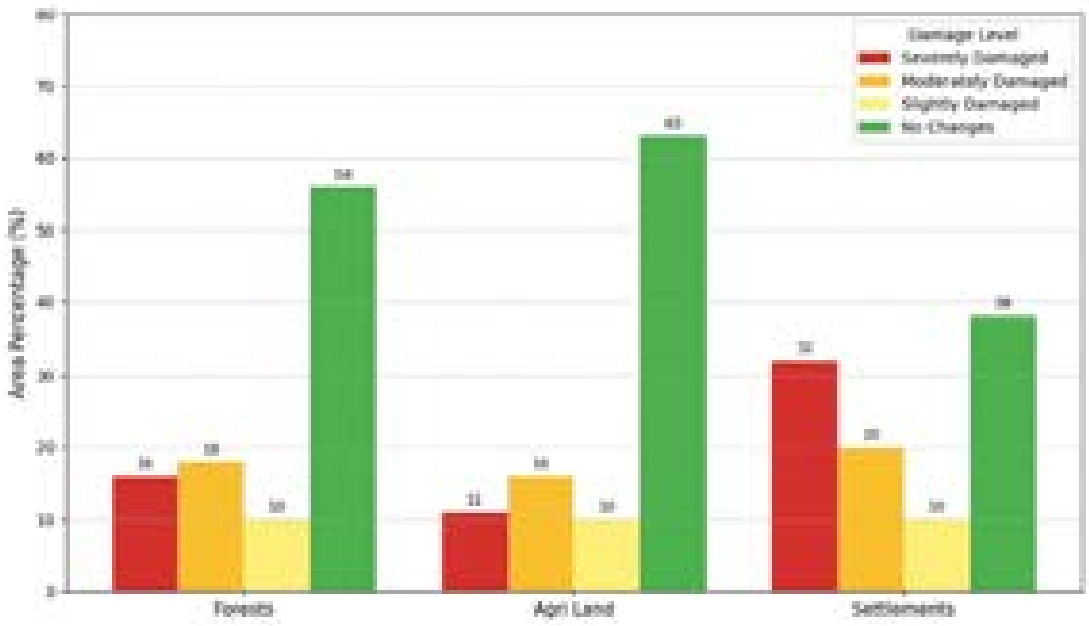


Fig. 8. Distribution of damage by type of territory

scientific interest is the comparative dynamics of recent years, which demonstrates the absence of the expected natural regeneration. Despite the decrease in the number of new foci of destruction, the NDVI index did not return to baseline values, and a further increase in the share of damaged areas was recorded in the categories of agricultural lands and settlements. This confirms that the initial military strike, compounded by the park's prolonged presence on the active frontline and the continuous high-intensity military pressure in 2024–2025, triggered a mechanism of chronic degradation, where the cumulative effect of ongoing hostilities, soil contamination and destruction of microrelief prevails over the pace of restoration.

In forest areas, the total area of damage is formally stabilised at 45%, but qualitative analysis indicates deterioration in the internal structure of the ecosystem. The increase in the share of severely damaged areas to 16% is a consequence of the delayed death of trees that received critical damage in previous years and eventually perished by 2025. Processes of natural forest regeneration at forest edges are often blocked by habitat fragmentation and changes in soil chemical composition. At the same time, the area of damage on agricultural lands has reached 37 Since field cultivation has been halted due to mining, the detected vegetation gain observed by satellite in particular areas represents a pseudo-recovery effect. In fact, this reflects the process of aggressive ruderalization - the replacement of cultivated and typical steppe groups with invasive species, which, from the point of view of conservation, is a sign of landscape degradation.

The highest level of degradation persists in settlements and infrastructure facilities located in the buffer zone and adjacent territories, where damage covers 60-62 %. It is important to emphasize that the degradation of these neighbouring areas directly affects the ecosystem of the park itself through soil contamination and changes in the hydrological regime. The lack of restoration of buildings, combined with weather-related erosion of damaged structures, leads to a gradual transition from moderate destruction to severe destruction. The statistical ratio of damaged and unchanged areas, presented in Figure 10, confirms that an independent return of the ecosystem to the pre-war state in the short term is impossible. The ecosystem remains in an unstable equilibrium, with a pronounced trend towards further landscape fragmentation, which requires the development of specialised reclamation strategies and long-term monitoring of the biota.

The next step in the analysis is to examine the speed of spring awakening. This indicator is calculated as the slope of the NDVI curve from March to May. It demonstrates the "energy" of ecosystem regeneration: the higher this indicator, the faster the vegetation increases biomass after winter dormancy (Fig. 9).

Analysis of spring vegetation dynamics revealed nonlinear trends that require in-depth scientific interpretation. The abnormally high rate of NDVI growth in 2022 and 2024 (0.220-0.226 units/month versus the baseline of 0.160) does not indicate ecosystem regeneration but is due to a «low start» resulting from critical damage to the soil cover and mass ruderalization of territories. The rapid expansion of weeds in damaged areas creates the illusion of intensive growth, mathematically distorting bioproductivity indicators.

The most critical indicator is the year 2025, where the rate of spring awakening fell to a

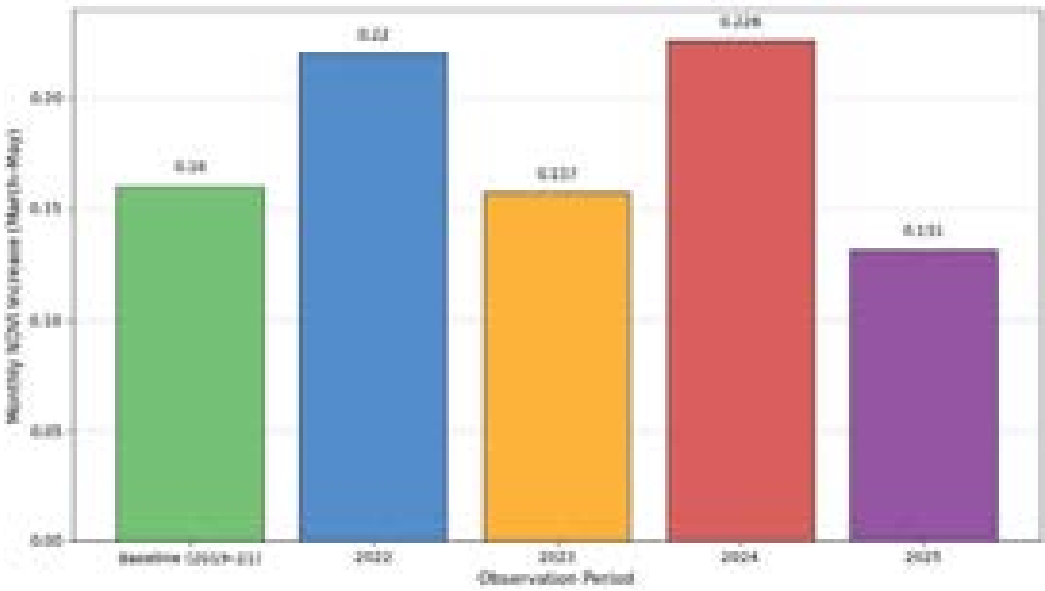


Fig. 9. Dynamics of the speed of spring vegetation of the Dvorichansky National Park from March to May (2019–2025)

Table 2

Approximate area calculation

Parameter	2021 (base)	2025 (current status)	Change
Area of exposed chalk outcrops	~42 hectares	~58 hectares	+28%
Turf Integrity Index on Slopes	0.85	0.62	-27%

historical minimum – 0.131 units/month, which is 18% lower than the pre-war standard. Such a decrease in vegetation's "energy" indicates a deep depletion of the ecosystem due to the toxic effects of ammunition residues, pollution from fuels and lubricants, and degradation of the hydrological network. The obtained data refute the hypothesis of the Dvorichanskyi National Park ecosystem's rapid self-recovery and indicate a progressive failure of natural regeneration mechanisms.

Special attention was paid to the analysis of the 10% of the park area with the worst vegetation condition (local degradation index based on the 10th percentile (P 10 NDVI) in order to see the real destruction that is «hidden» behind the overall average figures. As it turned out, in the most damaged areas (sites of explosions, fires, and fortification construction), vegetation levels fell by 14% compared to pre-war levels. This indicates the emergence of stable «dead zones» where nature cannot recover at all due to critical poisoning and physical destruction of the soil. Such a significant drop in the index for already vulnerable areas confirms that the war created foci of complete ecological transformation that will require decades for rehabilitation.

The destabilisation of the Cretaceous outcrops poses a critical threat to the protected area. While in 2021 these ecosystems were in a state of equilibrium, monitoring in 2024–2025 documented a transition from destruction to self-sustaining degradation. On the chalk slopes, direct hits of ammunition in soft rock created craters, which, under the influence of precipitation, transformed into an extensive network of erosion furrows and ravines. Furthermore, severe fires that occurred in the park in 2023 and 2024 destroyed the protective vegetation cover, significantly contributing to the exposure of these slopes. This led to a 38% increase in the area of exposed substrate (Table 2) and an irreversible change in the relief.

To quantify these processes, the pixel segmentation method based on brightness and vegetation activity thresholds (NDVI ≤ 0.12) and spatial connectivity analysis (Connectivity Analysis) was used. The resulting turf integrity index reflects the continuity of the protective biological layer of petrophyte steppes. Its steady decrease from 0.85 to 0.62 (Fig. 10) mathematically confirms the disruption of the connectivity of the flora roots, which makes the slopes vulnerable to further erosion regardless of the intensity of new hostilities.

Fragmentation of vegetation cover poses a direct threat to the survival of narrowly endemic and relict species, such as chalk hyssop (Hyssopus cretaceus), limestone thyme (Thymus calcareus) and thin-leaved peony (Paeonia tenuifolia). Since these species are adapted to stable substrates with slow soil formation, the physical destruction of their habitats results in a qualitative degradation of their floristic composition. Bare chalk areas serve as entry points for the expansion of

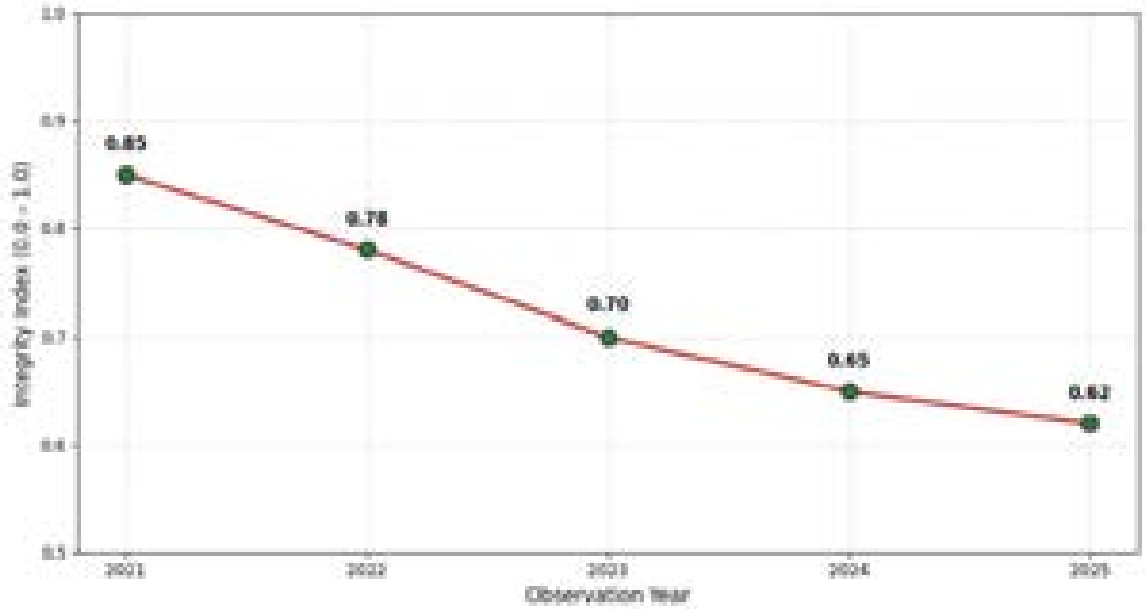


Fig. 10. Dynamics of the turf integrity index of chalk slopes of the Dvorichansky National Park for the period 2021–2025.

aggressive ruderal species, threatening the local extinction of populations listed in the Red Book of Ukraine and the European Red List.

The objectivity of the identified degradation processes was confirmed by a statistical test of the significance of differences in NDVI indicators between the pre-war (2019–2021) and military (2022–2025) periods. The use of a paired t-test yielded a p-value of < 0.05, providing grounds to reject the null hypothesis of random changes. This mathematically proves that the recorded decrease in bioproductivity of the Dvorichanskyi National Park is statistically significant and directly caused by intense military pressure. The calculated confidence interval confirms the stability of the negative trend, which extends the monitoring results beyond the limits of the ecosystem's natural variability and finally verifies the deep transformation of landscapes under the influence of military actions.

Discussion. Conceptual model of ecosystem degradation of the Dvorichansky National Park. Based on the data obtained, we developed a model of the cascading transformation of the reserve ecosystem under the influence of military actions (Fig. 11).

The central element of the model is the distinction between direct and indirect factors

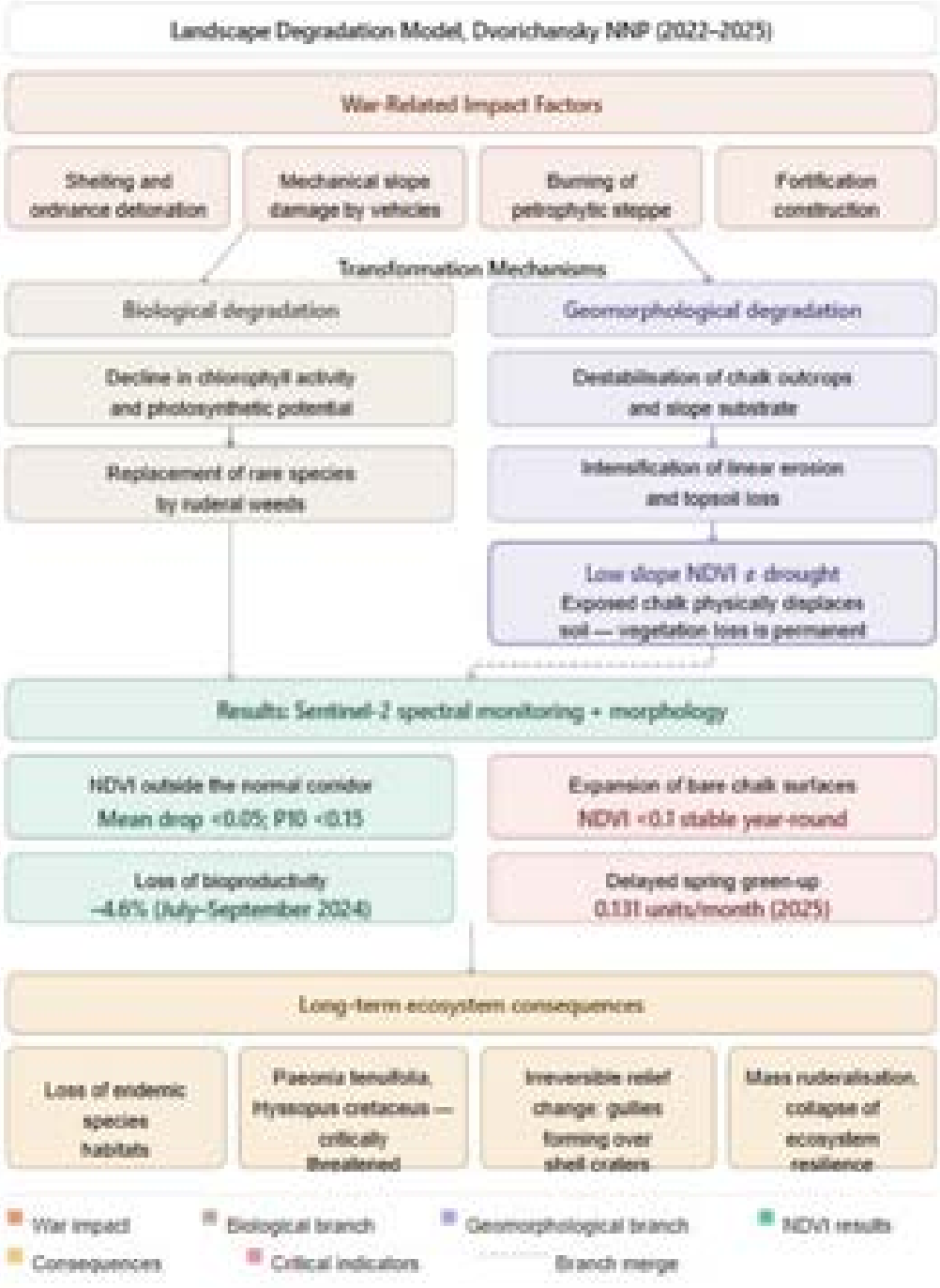


Fig. 11. Conceptual model of the transformation of protected ecosystems under the influence of military factors

that trigger mechanisms of long-term belligerent transformation of the landscape. Direct impact, including mechanical destruction of the soil cover and explosive deformations, leads to an immediate decrease in bioproductivity, as we clearly observed in the NDVI index. However, secondary processes, such as the activation of linear erosion on chalk slopes and chemical poisoning of the substrate by detonation products, are more dangerous.

The model demonstrates that vegetation damage triggers a chain reaction: the destruction of turf exposes soft rock, which, under the influence of precipitation, leads to irreversible changes in relief and habitat fragmentation. Statistically significant t-test results confirm that this process has gone beyond the limits of natural variability. An important aspect of the model is the effect of pseudo-recovery through ruderalization - the replacement of autochthonous species by aggressive weeds. This explains why the visual stabilisation of NDVI in individual areas actually hides a deep qualitative degradation of biodiversity. Thus, the developed conceptual scheme emphasises that without active intervention and specialised reclamation strategies, the park ecosystem will remain trapped in a self-sustaining cycle of degradation, in which each subsequent vegetation cycle only deepens the existing structural changes.

Prospects for restoration and strategic risks. The complex degradation of vegetation in the Dvorichanskyi National Park has a long-term cascading impact on the entire ecosystem. In addition to the direct destruction of flora, the recorded drop in NDVI reflects a profound disruption of the hydrological balance and a change in the microclimate: the loss of vegetation cover reduces the area's ability to retain moisture, which is critical for arid steppe landscapes. A particular difficulty for future rehabilitation is the contamination of the area by mining. This not only poses an immediate danger but also makes it impossible to implement active environmental protection measures, such as controlling erosion on slopes or promoting natural forest regeneration.

Given the results obtained, further research should be directed towards the use of machine learning algorithms to automate the detection of belligerent transformations of ecosystems in frontline areas and to assess the long-term impact of chemical contamination of soils by detonation products. The development of strategies for targeted rehabilitation of the park should be based on an interdisciplinary approach that combines satellite monitoring with point-by-point field studies (after demining). This will allow moving from assessing damage to implementing scientifically sound plans for restoring the unique Cretaceous landscapes of the Kharkiv region.

Conclusions

Based on the results of the study, the following conclusions have been drawn:

1. Based on the analysis of Sentinel-2 satellite data, it was found that over the period 2021–2025, the ecosystems of the Dvorichansky National Park underwent a profound belligerent transformation. The total area of damaged areas increased to 46.5%, indicating that almost half of the reserve fund is now in a state of persistent ecological stress.

2. Anomalies in spring vegetation dynamics were revealed: high rates of NDVI growth in 2022 and 2024 were identified as a «pseudo-recovery» effect driven by massive ruderalization (weeding) of abandoned agricultural landscapes and craters. The 18% drop in vegetation rate in 2025, compared with the pre-war level, confirms the depletion of the ecosystem's adaptive potential.

3. Critical destabilisation of chalk outcrops was recorded: the area of bare substrate increased by 38%, and the turf integrity index fell from 0.85 to 0.62. This indicates a transition in erosion processes to a self-sustaining phase, threatening the destruction of the habitats of narrowly endemic flora species (Hyssopus cretaceus, Thymus calcareus).

4. Statistical verification using a paired t-test ($p < 0.05$) confirmed the significance of the identified deviations from natural variability, providing mathematical proof of a direct connection between military aggression and the systemic degradation of the park's landscapes.

5. The further restoration strategy for the Dvorichanskyi National Park should take into account the impossibility of short-term natural regeneration. It will require long-term satellite monitoring to identify priority reclamation areas after demining.

The research conducted lays the foundation for further scientific work and the formation of a strategy for the ecological restoration of Ukraine in the post-conflict period.

Внесок авторів: всі автори зробили рівний внесок у цю роботу
Конфлікт інтересів: автори повідомляють про відсутність конфлікту інтересів
Декларація про використання генеративного штучного інтелекту: Автори використовували інструменти генеративного штучного інтелекту (GenAI) для допоміжної роботи:

Author Contributions: All authors contributed equally to this work
Conflict of Interest: The authors declare no conflict of interest
Declaration of use of generative artificial intelligence: The authors utilized generative artificial intelligence (GenAI) tools in a supportive capacity: DeepL and Grammarly models were involved to verify the correctness of the text translation, as well as

моделі DeepL та Grammarly були залучені для перевірки правильності перекладу тексту, а також для виправлення граматичних та стилістичних помилок. Усі результати роботи з цими інструментами були ретельно контрольовані, перевірені та, за необхідності, відредаговані авторами. Автори несуть повну відповідальність за зміст та цілісність публікації.

to correct grammatical and stylistic errors. All outputs from these tools were carefully supervised, reviewed, and, where necessary, edited by the authors. The authors retain full responsibility for the content and integrity of the publication.

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Белігеративна трансформація заповідних екосистем Дворічанського національного природного парку та його околиць за даними дистанційного зондування

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АНОТАЦІЯ

Повномасштабна військова агресія на сході України спричинила безпрецедентний тиск на заповідні екосистеми, що вимагає об'єктивної оцінки завданої шкоди для розробки стратегій відновлення. Робота спрямована на виявлення просторово-

часової динаміки рослинності, аналіз дестабілізації унікальних крейдових відслонень та математичне підтвердження статистичної значущості трансформації природних комплексів під впливом військових факторів. Дослідження сприяє реалізації Цілей сталого розвитку ООН 13 та 15, забезпечуючи наукове підґрунтя для розробки стратегій відновлення екосистем. Військова агресія на сході України суттєво вплинула на заповідні екосистеми, що зумовлює необхідність об'єктивної оцінки збитків для планування заходів з відновлення. Це дослідження оцінює белігеративну трансформацію Дворічанського національного природного парку та прилеглих територій за період 2021–2025 років із використанням методів дистанційного зондування. Наша робота визначає просторово-часову динаміку рослинності, аналізує дестабілізацію крейдових відслонень і статистично підтверджує трансформацію екосистем внаслідок впливу військових факторів. Аналіз даних супутника Sentinel-2 за 2021–2025 роки виявив трансформацію 46,5% досліджуваної території (Дворічанський національний природний парк та його околиці). Найбільших пошкоджень зазнали забудовані території (62%) та лісові масиви (45%), розташовані на прилеглих землях. У лісах частка сильних пошкоджень зросла до 16% через відкладену загибель дерев. На покинутих полях спостерігався ефект «псевдовідновлення»: у 2022–2024 роках індекс NDVI штучно підвищувався через масову рудералізацію (забур'янення), але вже у 2025 році рівень рослинності впав на 18% нижче довоєнного рівня, що свідчить про виснаження ґрунту. На крейдових схилах площа оголених порід збільшилася на 38% (з 42 до 58 гектарів). Вибухи та порушення цілісності дерну призвели до зниження індексу цілісності з 0,85 до 0,62, що спровокувало активну лінійну ерозію та утворення ярів. Статистична перевірка (парний t-критерій, $p < 0,05$) підтверджує, що ці зміни є результатом саме військового впливу, а не природних коливань. Наша модель трансформації ілюструє, як первинні пошкодження запускають каскадні, незворотні процеси ерозії та хімічної деградації.

ІНФОРМАЦІЯ ПРО СТАТТЮ :

Рукопис надійшов
15 лютого 2026

Отримано після рецензування
27 квітня 2026

Затверджено до друку
25 травня 2026

Опубліковано онлайн
30 травня 2026

Ключові слова:

дистанційне зондування, індекс NDVI, ерозія ґрунту, військовий вплив, індекс цілісності дерну, ландшафтна трансформація, деградація рослинності, цілі сталого розвитку ООН.

https://doi.org/10.26565/2410-7360-2026-64-15

UDC 711.4:349.4(477)

Navigating Ukraine's spatial planning framework: legal foundations and new priorities

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ABSTRACT

Introduction. The full-scale war has fundamentally transformed the context of spatial development in Ukraine and exposed significant weaknesses in the legal and institutional framework governing spatial planning and urban development. Against the backdrop of Ukraine's European integration process, the modernisation of spatial planning legislation has become an important prerequisite for improving governance, strengthening territorial resilience, and ensuring the coordinated recovery of communities. This research aims to critically examine Ukraine's current legislative framework for spatial planning and urban development, identify its strengths and weaknesses, and define strategic directions for its renewal in line with Ukraine's key needs and challenges.

Methods. The study is based on a comprehensive analysis of Ukrainian legislation, policy documents, and academic literature on spatial planning and urban development, combined with a comparative assessment of their alignment with European planning approaches and emerging priorities of post-war reconstruction. Content analysis identified gaps in the legal framework for spatial planning, while a SWOT analysis assessed the strengths and weaknesses of the current spatial planning system.

Results. The research reveals that current legislation remains fragmented and complex, hampered by martial law, war-related destruction, and a lack of coordination between government sectors. Major issues include the limited public access to geospatial data and challenges in managing urban development processes, especially in the context of post-war reconstruction. The findings suggest that modernising Ukrainian spatial planning legislation can be achieved by integrating post-war reconstruction priorities, housing strategies, and geospatial solutions into a single, sustainable spatial development system. Housing reform is identified as a critical component for protecting the rights of internally displaced persons through restoration, compensation, and strategic investment. At the same time, effective integration with geospatial infrastructure requires harmonised data standards, technical interoperability, and stronger alignment with hromada-level planning processes. The analysis further demonstrates that transforming the legislative framework should optimise mechanisms for preparing key spatial planning documents, particularly the Comprehensive Plan for the Spatial Development of the Territorial Community, while strengthening territorial hromadas' capacity to use spatial resources efficiently and respond to economic instability.

Conclusions. The modernisation of Ukraine's spatial planning system requires the integrated alignment of legislation, institutions, housing policy, and geospatial technologies, while drawing on European planning experience to enhance the resilience, inclusiveness, and sustainability of post-war recovery. The proposed reforms would contribute to more effective territorial governance, improved planning practices, and stronger adaptive capacities of communities facing long-term demographic, economic, and infrastructure-related challenges. This research aligns with the United Nations Sustainable Development Goals, particularly SDG 11 (Sustainable Cities and Communities), SDG 9 (Industry, Innovation and Infrastructure), and SDG 16 (Peace, Justice and Strong Institutions), emphasising the importance of resilient, inclusive, and sustainable spatial development in post-war Ukraine.

ARTICLE INFO

Manuscript received
20 January 2026

Revised manuscript received
18 March 2026

Manuscript accepted
25 May 2026

Available online
30 May 2026

Keywords:

spatial planning, legislation, post-war recovery, housing policy, urban planning, sustainable development, territorial community (hromada), Ukraine.

In cites: Malchykova Daria, Šilhánková Vladimíra (2026). Navigating Ukraine's spatial planning framework: legal foundations and new priorities. *Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology*, (64), 192–203. https://doi.org/10.26565/2410-7360-2026-64-15

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Introduction

The post-war reconstruction of Ukraine raises unprecedented challenges for spatial planning and urban development (Maruniak et al, 2024). The destruction caused by the full-scale invasion, combined with demographic changes and economic instability, has created conditions that are prompting a reevaluation of approaches to territorial management (Ilyniak, 2024; Malchykova, 2025), as well as spatial development and planning (Libanova & Bystriakov, 2025; Maruniak et al, 2022). Legislation on spatial planning in Ukraine remains fragmented and complicated, often failing to coordinate with other government sectors and lacking a unified basis for sustainable development (Ohorodnyk et al, 2025). This fragmentation is particularly problematic in a state of martial law, when crisis decision-making and resource allocation are crucial for the recovery of communities and infrastructure.

Over the past decade, Ukraine has been gradually transitioning from the post-Soviet planning paradigm to European Union standards, reflecting broader aspirations for integration into the European model of spatial development (Anisimov et al, 2024a). However, this transformation is incomplete. Although legislative reforms have introduced new instruments such as integrated development strategies and digital planning tools, gaps remain in harmonisation, institutional capacity and practical implementation between EU policy and spatial planning. The most significant EU policies related to spatial planning have a profound impact on planning, but with varying effects on cities and regions across Europe (Purkarthofer, 2024). Ukraine continues to update its legislative framework for spatial policy and spatial planning practices in cities and regions. This study offers a comprehensive review of the transformation and current state of the regulatory framework for spatial planning in Ukraine.

Analysis of recent research and publications

After gaining independence in 1991, Ukraine began developing its own regulatory and legal framework for spatial planning, architecture, and construction. The first fundamental step was the adoption of the Law of Ukraine "On the Fundamentals of Urban Planning" in 1992, which initiated the transition from the centralised Soviet model to a more flexible system of territorial development management. The law laid the foundations for decentralising power, giving local authorities greater autonomy in planning matters. However, significant dependence on the central government remained, and public participation remained formal for a long time (Ohorodnyk & Markina, 2021).

The Law of Ukraine "On Regulation of City Planning Activity", adopted in 2011, was the first attempt to integrate the UN's global principles of sustainable development and initiated the transition to public management in urban development. It ensured transparency in procedures, facilitated public participation, promoted the rational use of resources, and integrated environmental standards into the planning process. This key piece of legislation illustrates the complex history of regulatory document updates caused by contemporary challenges. Since its adoption in 2011, this document has undergone at least 40 revisions as of August 2025.

The main periods of updating were related to:

2011–2015: active adjustments after the adoption of the law, in particular regarding approval procedures, control and terminology.

2016–2020: clarification of the powers of authorities, integration with other laws (land, environmental law), updates in connection with the reform of the administrative-territorial structure and decentralisation processes.

2021–2025: changes related to martial law, digitalisation, the creation of the State Inspectorate of Architecture and Urban Planning to replace the State Architectural and Construction Inspectorate, the introduction of a unified state electronic system in the construction field, etc.

In general, a distinctive feature of the development of administrative and legal regulation in the field of spatial planning and development has been the focus on the irreversibility of Ukraine's European course and advanced foreign experience, which gives priority to human rights and freedoms as factors of legal regulation in this area (Leschynsky, 2020; Onyskovets, 2024). Further reform of the current urban planning and land legislation, in particular the Law of Ukraine "On Amendments to Certain Laws of Ukraine Regarding Priority Measures for Reforming the Urban Planning Sector" (https://zakon.rada.gov.ua/laws/show/2254-20#Text), has led to a noticeable increase in the importance of spatial planning as a powerful tool for taking into account the interests of all stakeholders in the use of territorial resources (Ohorodnyk & Markina, 2021). At the national level, the transition from international UN documents and general abstract principles of the concept of "sustainable development" to the level of state legislation in Ukraine, the definition of priorities for the implementation of the Sustainable Development Goal Sustainable Cities and Communities", to specific action plans of local authorities, including local and professional communities, continues (Blinova & Rodyk, 2024).

Given Ukraine's contemporary spatial planning orientation towards implementing European principles, it is also essential to outline the conceptual foundations underlying

these principles. Territorial cohesion is an essential element that emphasises the need to reduce disparities between regions and places the territorial dimension at the forefront of political decision-making. It is followed by the principle of polycentricity, which supports the development of networks of cities and functional regions rather than the unilateral dominance of large metropolises. This approach enables a more equitable distribution of economic growth, services, and opportunities. Another key element is integrated place-based development, which requires strategies tailored to specific local conditions and resources. These strategies must link economic, social, and environmental aspects, as universal, one-size-fits-all solutions cannot respond to the territory's diversity. This is closely linked to multi-level governance and the principle of subsidiarity, which emphasises coordination between EU levels, national governments, regions, and municipalities, while the actual planning and implementation of measures remains largely the responsibility of Member States and local authorities. (Sommese et al., 2025).

In addition to these basic principles, several key topics are currently the focus of European spatial planning. These are in particular:

1) sustainable green adaptation, which combines environmental, social, and technical aspects. Nature-based solutions and multifunctional elements are a key component, bringing a wide range of benefits – from promoting biodiversity to mitigating flood risks, cooling the urban environment, and strengthening social cohesion. (Field & Bakker, 2021)

2) The concept of smart cities and digital transformation is a dynamically developing area that connects technological innovation with the goals of sustainable urban development. Digital twins and BIM methods play a crucial role in facilitating the adaptation of technical innovations to local conditions. At the same time, digital transformation is increasingly linked to nature-based solutions and circular economy principles, supporting environmental goals. This includes, for example, modelling the impacts of green infrastructure or optimising energy systems. This integrated approach shows that digitalisation can be a powerful tool for achieving environmentally and socially sustainable cities. (Patrascu, 2023; De Frantz, 2022).

3) Urban governance and participation are a dynamic area that brings together different levels of governance, actors, and thematic priorities. Stakeholder partnerships and co-creation processes are at the core of the Urban Agenda for the EU mechanism. Their aim is to mobilise cities, regions, civil society, and the private sector to work together in thematically focused partnerships that allow for the sharing of experiences and the joint search for solutions. (Patrascu, 2029; Field & Bakker, 2021)

In addition to the above principles and thematic areas, it is important to mention specific European mechanisms and tools that have already been introduced in EU countries and represent a standard for the effective performance of spatial planning, and their implementation in the Ukrainian environment is still only partially or not systematically. These are in particular:

1) Implementation of the INSPIRE Directive – i.e. full interoperability of spatial data of public administration across sectors, the obligation to provide open data in standardised formats and interconnection with thematic data sets (environment, transport, infrastructure, territorial limits). In EU countries, INSPIRE is a basic prerequisite for a unified data "ecosystem" of planning (European Parliament & Council, 2007), while in Ukraine, data harmonisation remains in its early stages and there is a lack of institutional capacity for its widespread implementation.

2) Strategic Environmental Assessment (SEA) and its binding interconnection with all levels of spatial planning. In the EU, it is impossible to approve strategy papers without an SEA, and the SEA conclusions are legally binding (European Parliament & Council, 2001). In Ukrainian practice, SEA implementation remains only partially effective: the procedure is often carried out in a formal manner, its findings are poorly integrated into zoning plans and other spatial planning documents, and institutional and procedural gaps continue to limit the enforceability of SEA requirements.

3) Binding EU multilevel governance – i.e. a clear link between the EU level, state, region and municipality, including vertical and horizontal coordination mechanisms. In the EU, this coordination is ensured through structural policy, ESDP rules, the Urban Agenda for the EU, or mandatory compliance with funding programmes. However, Ukraine still lacks a binding mechanism to ensure that regional and local documents truly align with state priorities and do not conflict with one another.

4) Integrated Territorial Investment (ITI) and Community-Led Local Development (CLLD) as established EU instruments for functional regional cooperation. These support urban and metropolitan areas in addressing common issues (mobility, housing, infrastructure) (European Parliament & Council, 2013). In the Ukrainian environment, the functional level of planning is still under development and there are no financial and legal instruments to implement it.

5) Binding mechanisms for monitoring and evaluation of spatial plans, which are regularly implemented in the European Union (typically every 4-6 years) and have a direct impact on the updating of strategic and spatial plans (e.g. Czech Republic, 2021; Germany, 2025). However, in

Ukraine, monitoring is not systematised, and there is no common methodology for its implementation.

These European instruments show that European integration in the field of spatial planning is not just a matter of accepting principles, but requires institutional capacity, technical standards, cross-sectoral coordination and legally binding mechanisms that enable them to be put into practice. Their introduction in the Ukrainian context thus represents not only a technical but, above all, an institutional challenge, which further strengthens the argument for deeper, systemic institutional reform.

Despite positive developments and efforts to make the legislative framework systematic, adaptive, and effective, legislation on various aspects of spatial planning in Ukraine addresses detailed issues in a chaotic, uncoordinated manner (Nowak et al., 2023), complicating its practical application. The lack of a unified Urban Development Code, insufficient coordination between strategic and urban development documents, and the formal nature of community participation require a systematic solution.

Objective and methods

The research aimed to critically assess the current state of the legal framework for spatial and urban planning in Ukraine, identify its strengths and weaknesses, and define strategic directions for its renewal in line with Ukraine's key needs and challenges.

The study is grounded in the principles of systems analysis and an integrated approach to spatial planning, combining legal, economic, social, and institutional analysis. The methodology is based on a comparative analysis of existing Ukrainian laws in the fields of urban development and spatial planning, as well as subordinate legislation, strategic documents on spatial development, and post-war reconstruction. Content analysis identified gaps, duplications, and conflicts in the legal framework for spatial planning, while a SWOT analysis assessed the strengths and weaknesses of the current spatial planning system.

Results

The current structure of regulatory and legal documents governing spatial planning, architecture, and construction in Ukraine is hierarchical in both spatial and regulatory (normative) contexts. The spatial hierarchy traditionally reflects the spatial scale of document action, which today corresponds to the levels of Ukraine's administrative-territorial structure (Table 1). Each level has its own objectives, powers, and types of documentation, which must be coordinated with one another, both "top-down" and "bottom-up".

The regulatory (normative) hierarchy (Table 2) determines the legal force and binding nature of documents.

This hierarchical structure is designed to ensure consistency in spatial planning, establish clear powers for each level of government, and guarantee consistency between documents at different levels. At the same time, "spatial" documents serve as instruments for implementing strategies enshrined in legislation, while "regulatory" documents are used to monitor their implementation. The regulatory framework has evolved over the past 30 years in response to new challenges, such as decentralisation, digitalisation, martial law, European integration, etc. (Fig. 1.)

Additionally, for a long time, one of the key national-level urban planning documents was

Table 1

The spatial hierarchy of documents governing spatial planning, architecture, and construction in Ukraine

Spatial hierarchy level	Documents
State	General Scheme for Planning the Ukrainian Territory, State Regional Development Strategy
Regional	Regional planning schemes, regional development strategies
Local (communities)	General Plan of the Settlement, Comprehensive plan for the spatial development of the territory of the territorial community, Detailed plans of territories, etc.

Table 2

The hierarchy of regulatory and legal documents governing spatial planning, architecture, and construction in Ukraine

Regulatory hierarchy level	Documents
Constitutional/legislative	Constitution of Ukraine, laws (On the Fundamentals of Urban Planning, On the Regulation of Urban Planning Activities)
Subordinate	Resolutions of the Cabinet of Ministers of Ukraine, orders of ministries (e.g., Ministry for Development of Communities and Territories of Ukraine)
Regulatory and technical	State Building Codes of Ukraine (DBN), standards
Methodological/ recommendatory	Methodological recommendations, instructions, local regulations



Fig. 1. Key Reform Drivers in Spatial Planning Legislation

the General Scheme for Planning the Ukrainian Territory, serving as both a planning tool and a document outlining the conceptual decisions for planning and land use in Ukraine. The Law of Ukraine "On the General Scheme for Planning the Ukrainian Territory" outlined the development, implementation, and monitoring process. According to legislation, the General Scheme was initially designed for a 20-year period and is no longer valid. In 2020, a draft law proposing amendments to the Law of Ukraine "On Regulation of City Planning Activity" to update the General Scheme was registered but remains in a parliamentary committee (Anisimov et al., 2024b).

An important milestone in the reform of the legislative framework for land use planning was Law of Ukraine (2020) "On Amendments to Certain Legislative Acts of Ukraine Regarding Land Use Planning", which was the first in the history of Ukrainian land legislation to regulate social relations regarding comprehensive land use planning (Shulga et al, 2025). The law defined five major legislative innovations to the Land Code of Ukraine, the Law of Ukraine "On Regulation of City Planning Activity", the Law of Ukraine "On Land Management" and other normative acts:

1) zoning of land within the territories of territorial communities and the development of a single document combining urban planning and land management documentation – a Comprehensive plan for the spatial development of the territory of the territorial community;

2) the disappearance of "types of land use" and the emergence of "functional purpose of territories";

3) the intended purpose within the functional purpose of the territory is determined by the landowner independently and does not require the development of a land management project;

4) a citizen who wishes to privatise a land plot free of charge or obtain state or communal land plots for use submits an application to the competent authority in electronic form via the Public Cadastral Map;

5) restrictions and encumbrances on the use of land plots necessary for the placement of objects may be established for up to 10 years and may be forcibly alienated. This Law also regulated the following key changes in the field of spatial planning and development:

• the development of new urban planning documentation – a Comprehensive plan for the spatial development, which will determine the requirements for the use of the territory both within and outside settlements;

• giving the Comprehensive plan for the spatial development, General Plan of the Settlement, and Detailed plan of territory, the status not only of urban planning documentation, but also of land management documentation;

• enabling, with the help of a Comprehensive plan, a master plan for a settlement, and a detailed plan: the formation of communal land plots; the entry of information about land plots formed before 2004 into the State Land Cadastre; the entry of information about restrictions on land use into the cadastre;

• entering planning restrictions established by urban planning documentation ("red", "yellow", "green" lines, etc.) into the State Land Cadastre;

• reserving land necessary for the construction of public facilities (roads, bridges, power lines, etc.);

• the possibility for communities to establish their own urban planning and architecture bodies, which will be able to issue urban planning conditions and restrictions throughout the hromada;

• the possibility of changing the intended use of privately owned land plots without developing land management projects for their allocation, if the new intended use is consistent with the functional zoning of the territory defined by urban planning documentation;

• an increase in the amount of agricultural production losses paid to local budgets when changing the intended use of agricultural land plots (30% of the difference in the normative

monetary valuation of land plots after and before the change in intended use);

• enshrining in the Water and Land Codes of Ukraine provisions according to which coastal protection strips are established by operation of law without needing additional documentation.

Notably, despite significant advances in the practical aspects of spatial planning, the conceptual definition of the term "spatial planning" remains absent from Ukrainian legislation (Markina, 2023). Instead, "urban development" or "urban development activities" are used. Accordingly, legally binding plans and documents specified in the Law of Ukraine "On Regulation of City Planning Activity" are referred to as "urban planning documentation" (Anisimov et al, 2024b). At the same time, all other instruments, particularly the Integrated Development Concept of the Territorial Community and the Community Strategic Plan, are not considered urban planning documentation. Ukrainian legislation has laid the foundation for common approaches to the formation of key documents for spatial and economic planning of the development of territorial communities, the unity of land management and urban planning documentation at the local level, and the interrelated formation of three systemic key planning documents: Comprehensive plan for the spatial development of the territory of the territorial community, Integrated Development Concept of the Territorial Community, and Community Strategic Plan (Oleksyuk et al, 2021). However, researchers (Kravchenko et al, 2024; Hnatkovych et al, 2023) note the lack of systematic forecasting and long-term strategic planning for the country's development, insufficiently defined links and coordination mechanisms between strategic documents, and the absence of precise and uniform standards, procedures and distribution of functions between government and other entities in the process of state strategic planning, including spatial planning.

The discourse on the legislative and regulatory framework for spatial planning in Ukraine at the present stage reveals several important features.

Firstly, Ukrainian legislation in the fields of planning and construction has historically been complex and inconsistent. Even before the war, it underwent significant reforms, caught between two vectors (Anisimov et al., 2024a): Europeanisation (the introduction of principles of transparency, sustainable development, and community participation) and post-socialist inertia (the dominance of economic imperatives and weak law enforcement). In 2011, changes to the legislation were adopted, making public participation in the planning process mandatory and requiring the publication of public plans. Since 2014, a targeted increase in local councils' fiscal and administrative capacities, along with decentralisation reform, has created the conditions for full self-government at the local level, culminating in the transfer of control and responsibility for land and spatial planning from state administrations to local self-government bodies. With the system's renewal, comprehensive planning was introduced at the local level for the entire territory of territorial communities. Following this shift, planning gradually transformed from an instrument for implementing state interests into a mechanism for harmonising the interests of the public, the private sector and the state (Lytvynchuk et al, 2022).

The main changes in the pre-war years of 2020-2021 included the introduction of Comprehensive plans for the spatial development at the hromada level and the creation of a Unified State Electronic System for the Construction. However, the sector faces challenges such as a lack of explicit codification, insufficient public access to geospatial data, and difficulties in managing chaotic urban development, especially in post-war reconstruction (Kvasnitska, 2023). In this regard, several legislative acts have been added to the key documents in urban development/spatial planning, ensuring the post-war recovery and reconstruction process.

Secondly, the process of reforming the regulatory framework in the field of spatial planning, urban development and architecture at the present stage is influenced by three key factors: a) the continuation of decentralisation reform; b) the challenges of martial law and meeting the needs of post-war reconstruction; c) bringing Ukraine's legislative framework in the field of urban development and land use regulation into line with the norms and practices of the European Union. A comprehensive analysis using the SWOT methodology (Table 3) revealed that Ukraine's regulatory framework for spatial planning requires structural updates, systematisation, and integration with contemporary challenges, while also presenting several strengths and opportunities for innovative development.

Thus, the focus on harmonisation with European Union standards and further decentralisation has led to the development of an innovative document in spatial planning and the codification of urban planning legislation — the new Urban Planning Code of Ukraine. The first version of the Concept of the Urban Development Code of Ukraine was developed in 2023, its urgent need being justified by the frequency and number of specific amendments to laws, the multiplicity of urban planning legislation, and numerous gaps and inaccuracies in the existing regulatory framework (Balashova, 2023). It was published at the end of September 2025 as the "Concept of the Code of Spatial Planning and Development of Territories (Urban Development Code of Ukraine)" (Concept of the Code..., 2025) - a comprehensive systematic review of the legal norms governing urban planning and related areas that affect it, as well as economic mechanisms for implementing the main directions of change.

Table 3

SWOT analysis of Ukraine's legislative framework in the field of planning and construction in the context of contemporary challenges

Strengths	Weaknesses
Adaptability to wartime conditions: Adopted laws permit changes in land use without requiring complete urban planning documentation.	Fragmented legislation: The absence of a single Urban Planning Code creates legal uncertainty and complicates coordination between authorities and investors.
Institutional reform: Creation of the State Architecture and Urban Planning Inspectorate to replace the State Architecture and Construction Inspectorate as part of Ukraine's construction industry reform to overcome corruption, simplify procedures, and digitise urban planning processes.	Temporary nature of decisions: Excessive dependence on detailed territorial plans (DTPs) in wartime does not ensure long-term stability.
Digitisation: The introduction of electronic urban planning cadastre registers and online permitting procedures simplifies access to information, reduces bureaucracy and increases transparency.	Risks to property rights: New provisions on «future objects» may create legal conflicts, particularly in unfinished construction or in cases of the developer's bankruptcy.
Flexibility of planning tools: Utilising DPT as a temporary tool enables a quick response to reconstruction needs.	Insufficient community participation: The formal nature of consultations undermines trust in the planning process.
Opportunities	Threats
Reconstruction of de-occupied territories: Opportunity to create a new quality of spatial planning.	Delays in reforms: Lack of political will slow the adoption of the Urban Development Code and other key changes.
European integration: Harmonisation with EU standards (in particular the INSPIRE, SEA and EIA directives) opens up access to funding and expert support.	Legal uncertainty: Conflicts among land-use, urban planning, and investment legislation may create barriers to project implementation.
Finalising the Urban Development Code as soon as possible will unify fragmented regulations and ensure the stability of the legal framework.	Military risks: Prolonged warfare complicates strategic planning, particularly in combat zones, border areas, and formerly occupied regions. The reconstruction of de-occupied territories requires simplified procedures and a clear regulatory framework that account for social, environmental, and cultural factors.
Investment attractiveness: Introducing escrow accounts and digital services helps attract capital.	Uneven digitalisation: Some communities' lack of technical capacity may lead to unequal access to new tools.

The principle of "Build Back Better" for war-torn Ukraine (Shevchenko et al, 2025) is implemented in the Concept through civilised procedures and clear rules, as well as new approaches to spatial planning, economic guarantees of independence for liberal professions, the circular economy, and environmental requirements. The new rules to be established by the Urban Development Code will allow for planning and building "better than before" not only in reconstruction processes, but also in "normal" construction.

The main principle underlying the measures proposed by the concept is human-centred, as well as striking a balance of interests between urban development actors and fostering an open market of free individuals. This concept lays out the basic approaches to policy formation set out in the European Regional Spatial Planning Charter (Council of Europe, 1983), the European Charter of Local Self-Government (Council of Europe, 1985), the New Leipzig Charter "The transformative power of cities for the common good" (European Commission, 2020), the New Urban Agenda (United Nations, 2016), and the best European and American practices.

The key innovations are:

– a free development of competition is encouraged - strengthening competitive practices, copyright protection, professional risk insurance, the development of self-regulatory organisations in the field of urban development, which balances the responsibility of specialists established by law;

– a new, flexible approach to the formation of spatial planning documentation is proposed - what communities need here and now, as well as increased participation of residents in the formation of spatial plans by giving a leading role to self-organisation bodies of the population;

– the concept and procedures for the entire life cycle of a property have been introduced, from its appearance on the plan, through design, construction and operation, to liquidation, recycling of construction waste and freeing up space for future development.

– mechanisms for the revival of architectural restoration have been proposed in order to preserve cultural heritage and restore monuments damaged and destroyed as a result of Russian aggression;

– the concept of "public space" has been introduced as the embodiment of the democratic principles of our society;

– human-centred procedures laid down in the framework Law of Ukraine "On Administrative Procedures" have been implemented in special "urban planning" legislation, which will ensure compliance with the rule of law, equality before the law, the validity of decisions taken, the

impartiality (objectivity) of the administrative body, good faith and prudence, proportionality, openness, the timely provision of administrative services within a reasonable time frame, efficiency, the presumption of the legality of actions and claims of individuals, formality, guaranteeing the right of a person to participate in administrative proceedings and effective legal remedies.

This Concept was developed transparently and inclusively, based on the principle of bottom-up public policy formation. In general, the Concept contains proposals for resolving problematic issues in the following areas: spatial planning, design, construction, operation, liquidation of real estate objects, land management in urbanised areas, survey activities, restoration, ecology, improvement, heritage protection, archaeology, education, science, professional certification, housing construction, pricing, insurance, public procurement, financing, compensation, transport, and civil protection.

Digitalisation permeates all these areas of current reforms in Ukraine. For example, urbanisation drives Digital City Projects (DCPs) to create smarter urban environments using advanced technologies (Kostrikov et al., 2023). An innovative result of the accelerated digitalisation in planning and development over recent years has been the creation of the Unified State Electronic System for Construction (USESFC). This is a national digital platform that provides electronic management of all processes in the construction field, from planning to commissioning of facilities (Official portal: e-construction.gov.ua). Its introduction has led to a significant update of the national regulatory system in this area. It aligns with EU practices: fully digitised planning processes ("planning digital-by-default"), including the mandatory use of BIM and digital models of the territory in some types of documentation (e.g. Czech Republic, 2021; Germany, 2025). Although Ukraine has made significant progress with the USESFC system, there is a lack of uniform, binding digital standards, and the absence of legal obligations to link land-use plans to geospatial systems prevents their full use.

The USESFC consists of three main components: 1) a register of construction activities (containing data on construction projects, participants, permits, technical inventories, etc.); 2) a public portal accessible to all users (providing search, viewing, analytics and an interactive map of projects); 3) an electronic office (intended for officials, architects, engineers, developers, allowing them to submit documents, register objects, and track statuses).

Functionally, the USESFC provides 13 online services through the Diya portal, including: notification of the start of work, issuance of a construction passport, declaration of readiness for operation, permission to perform work, certificate of acceptance of the object into operation, automatic checks, integration with other registers (e.g., the register of damaged property, the DREAM system). The achievements of this system include registering over 7 million documents in 5 years, more than 140,000 users, introducing more than 80,000 urban planning conditions and restrictions, issuing 160,000 construction passports, and processing 713,000 permits.

Despite all the innovative achievements, the complex and hierarchical system of legislative regulation in spatial planning and construction today faces not only the challenges posed by martial law and the consequences of military action, but also those of cross-sectoral coordination with other areas of public life. A striking example of such topical scientific and practical areas within the framework of legal research is housing policy, as it has not been updated since 1995, while actual housing relations have already undergone significant changes. Research (Teremetskyi et al, 2024) supports the idea of distinguishing a separate area of contemporary housing policy in Ukraine, namely ensuring the housing rights of persons forcibly displaced by war in the following specific areas: restoration of housing facilities (such as construction of new housing, compensation for destroyed housing, and repair and construction work); development of an investment strategy for the housing sector; protection of citizens' housing rights; and revision of housing legislation. Libanova & Bystryakov (2025), drawing on general European trends, present an innovative vision of Ukraine's post-war spatial development to create an effective model for reconstructive organisation of socioeconomic activity. The novelty of the proposed approach lies in defining the conceptual foundations for structuring spatial entities to effectively utilise available territorial resources, emphasising the overcoming of economic system instability. Issues related to the mutual integration of the spatial planning and construction system and the National Geospatial Data Infrastructure remain under development. Integration with key urban planning documentation, particularly comprehensive spatial development plans for local communities, is a priority area, but it requires harmonising geospatial data specifications, developing interoperability standards, and providing technical and regulatory support.

The financial mechanisms of the European Union and their integration with spatial planning play a decisive role in ensuring effective reforms, as the combination of legislative changes with adequate budgetary support determines whether policies are implemented in practice rather than remain declaratory. In EU Member States, strategic and spatial planning is closely

linked to access to financial instruments – the European Regional Development Fund, the Cohesion Fund, the Just Transition Fund, as well as various models of cofinancing at municipal and macroregional levels. Strategies and plans may receive funding only if they comply with programme requirements, creating a clear connection between planning documents and budgeting procedures and ensuring coherence and transparency in spatial development policy.

In Ukraine, this link remains incomplete: stable co-financing mechanisms are lacking, the multi-fund approach is not applied, and most planning documents are not linked to financial instruments. At the same time, certain steps are being taken for instance, cofinancing schemes through the State Fund for Regional Development and recovery programmes involving local budgets and external donors. Promising instruments include subsidies for comprehensive spatial development plans, competitive infrastructure programmes, and municipal loan support, all of which can provide the financial foundation necessary for effective reform.

Thus, alignment with the European policy framework requires not only legislative approximation but also the development of robust institutional and financial mechanisms to ensure the real implementation of planning decisions and the transition to a modern spatial planning system.

Conclusions

Spatial planning legislation in Ukraine remains complex and fragmented, facing challenges not only from martial law and war-related destruction, but also from insufficient coordination with other public sectors. Ukraine has undergone a transformation of its post-Soviet planning approach, moving closer to European Union standards. This process should focus on several key dimensions: the institutional framework, legislative harmonisation and practical implementation.

Modernisation of Ukraine's spatial planning legislation is possible by integrating post-war recovery priorities, housing strategies, and geospatial solutions into a unified framework for sustainable spatial development, in particular:

– housing policy reform will allow the protection of the rights of internally displaced persons through restoration, compensation, legislative revision and strategic investments;

– integration with geospatial infrastructure is a strategic priority, requiring harmonisation of data standards, technical interoperability and coordination with integrated community planning;

– a new conceptual approach to post-war spatial development is focused on the capacity of territorial units to use resources efficiently and overcome economic instability, inspired by European models.

Подяка. Дослідження було підтримано в межах академічної програми 2025–2026 років для стипендіатів Virtual Ukraine Institute for Advanced Study (VUIAS). Автори висловлюють вдячність Інституту передових досліджень імені Масарика (Чеський технічний університет у Празі) за запрошення та фінансову підтримку участі в міжнародному семінарі «На шляху до сталого відновлення українських міст» (Towards a Sustainable Reconstruction of Ukrainian Cities), що відбувся в Чеському технічному університеті в Празі в жовтні 2025 року, а також за можливість представити на ньому основні результати цього дослідження.

Acknowledgments
Research was supported by the 2025/2026 academic program as a Fellow of the Virtual Ukraine Institute for Advanced Study (VUIAS). The authors gratefully acknowledge the Masaryk Institute of Advanced Studies (Czech Technical University in Prague) for the kind invitation and financial support to participate in and present the key findings of this research at the International Workshop "Towards a Sustainable Reconstruction of Ukrainian Cities," held at Czech Technical University in Prague in October 2025.

Внесок авторів: всі автори зробили рівний внесок у цю роботу
Конфлікт інтересів: автори повідомляють про відсутність конфлікту інтересів
Декларація про використання генеративного штучного інтелекту: Під час редакційного етапу використовувалися цифрові інструменти для покращення чіткості та стилю рукопису. Зокрема, для стилістичного вдосконалення та забезпечення відповідності академічним нормам використовувався Microsoft Copilot (GPT-4). Grammarly застосовувався для остаточного редагування мови, включаючи граматику, пунктуацію та стилістичну узгодженість.

Authors' Contribution: All authors have contributed equally to this work.
Conflict of Interest: The authors declare no conflict of interest.
Declaration of use of generative artificial intelligence: During the editorial phase, digital tools were employed to enhance the clarity and style of the manuscript. Specifically, Microsoft Copilot (GPT-4) was utilised for stylistic refinement and ensuring alignment with academic conventions. Grammarly was applied for final language editing, including grammar, punctuation, and stylistic consistency.

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Огляд системи просторового планування в Україні: правові основи та нові пріоритети

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АНОТАЦІЯ

У цьому дослідженні критично аналізується законодавча база України у сфері просторового планування та міського розвитку, визначаються її сильні та слабкі сторони, а також стратегічні напрямки оновлення у відповідь на післявоєнні виклики. Визначено, що чинне законодавство залишається фрагментарним і складним, обмеженим воєнним станом, руйнуваннями, пов'язаними з війною, та недостатньою координацією з іншими державними секторами. Ключовими проблемами залишається відсутність чіткої кодифікації, недостатній доступ громадськості до геопросторових даних та труднощі в управлінні хаотичним міським розвитком, особливо в контексті післявоєнної відбудови. Європеїзація українського законодавства у сфері просторового планування продовжується, проте потребує глибшої інституційної реформи, гармонізації законодавства та практичного впровадження. Обґрунтовується, що модернізація законодавства України у сфері просторового планування можлива шляхом інтеграції пріоритетів післявоєнного відновлення, житлових стратегій та геопросторових рішень в єдину систему для сталого просторового розвитку. Житлова реформа визначається необхідною для захисту прав внутрішньо переміщених осіб шляхом відновлення, компенсації та стратегічних інвестицій. Інтеграція з геопросторовою інфраструктурою потребує гармонізованих стандартів даних, технічної сумісності та узгодження з плануванням громади. Подальша трансформація законодавчого забезпечення просторового розвитку і практики планування повинна оптимізувати механізми підготовки ключових документів просторового розвитку, зокрема Комплексного плану просторового розвитку території територіальної громади, підвищити здатність територіальних громад ефективно використовувати просторові ресурси та долати економічну нестабільність, спираючись на європейські моделі просторового розвитку, забезпечуючи стійкість та сталий розвиток у післявоєнному контексті. Це дослідження відповідає Цілям сталого розвитку Організації Об'єднаних Націй, зокрема Цілям 11 («Сталі міста та громади»), 9 («Промисловість, інновації та інфраструктура») та 16 («Мир, справедливість та ефективні інститути»), підкреслюючи важливість стійкого, інклюзивного та сталого просторового розвитку в післявоєнній Україні.

ІНФОРМАЦІЯ ПРО СТАТТЮ :

Рукопис надійшов
20 квітня 2026

Отримано після рецензування
18 березня 2026

Затверджено до друку
25 травня 2026

Опубліковано онлайн
30 травня 2026

Ключові слова:

просторове планування, законодавство, післявоєнне відновлення, житлова політика, міське планування, сталий розвиток, територіальні громади, Україна.

https://doi.org/10.26565/2410-7360-2026-64-16

UDC 630*116:551.583

Anthropogenic changes in forest landscapes of Lake Sevan basin under climate change

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ABSTRACT

Statement of the problem. The paper analyzes the spatio-temporal dynamics of forest landscapes in the Lake Sevan basin. This area is one of the most sparsely forested regions of Armenia; moreover, its forests are generally of low productivity and limited industrial significance. A significant part of the forests (12.5 thousand hectares) is of artificial origin, while natural forests (around 3.0 thousand hectares) are mainly concentrated on the steep mountain slopes of the Areguni and Sevan mountain ranges, where oak and juniper communities prevail. Forests regulate climate through carbon storage and sequestration, cool land surfaces via water–energy cycling, sustain biodiversity, secure freshwater resources through hydrological regulation, reduce disaster risks, and contribute directly to livelihoods and public health. In the Lake Sevan basin, these functions should be considered from a multifunctional landscape perspective, because forest degradation affects not only tree cover but also hydrological regulation, soil stability, ecological connectivity, biodiversity, and the ecological condition of the lake.
The relevance. Lake Sevan is the largest freshwater system in Armenia, whose ecosystem stability largely depends on the balance and sustainable use of the basin's natural resources. The study is highly relevant for understanding current ecological transformations and supporting effective forest management and sustainable regional development.
The study aims to analyze and assess the patterns of anthropogenic change in the forest landscapes of the Lake Sevan basin, particularly under current climate change conditions.
The object of the study is the forest landscapes of the Lake Sevan basin.
The subject of the study is forest cover dynamics and the associated ecological risks.
Methods. The research was based on a combination of field observations, spatial analysis, and a review of published and institutional data. A geographical–comparative approach was applied, integrating map interpretation, statistical analysis, and semi-stationary field observations. The study included comparisons of historical and

ARTICLE INFO

Manuscript received
23 October 2025

Revised manuscript received
7 April 2026

Manuscript accepted
25 May 2026

Available online
30 May 2026

Keywords:

Armenia, Lake Sevan basin, forest dynamic, spatiotemporal patterns, anthropogenic changes, ice phenomena, deforestation, ecological balance, forest landscape restoration, ecosystem services, ecological resilience.

In cites: Margaryan Varduhi, Vila-Subirós Josep, Reshetchenko Svitlana, Avetisyan Gorik, Harutyunyan Elya (2026). Anthropogenic changes in forest landscapes of Lake Sevan basin under climate change. *Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology*, (64), 204–215. https://doi.org/10.26565/2410-7360-2026-64-16

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contemporary forest maps, assessment of forest cover dynamics, and identification of areas most affected by anthropogenic pressure. Quantitative assessments were complemented by field inspections that verified cartographic and remote sensing data. Additional information was obtained from the State Committee for Forestry, the Cadastre Committee, the Ministry of Environment of the Republic of Armenia, the Gegharkunik Regional Administration, and reports of international environmental organizations.

Results. Historically, the degree of afforestation in the region was considerably higher but has declined markedly due to long-term anthropogenic pressure. Deforestation has continued because of illegal and unregulated logging, together with the loss of flooded forest areas caused by fluctuations in Lake Sevan's water level. These processes threaten the ecological balance of the basin and underline the need for integrated scientific assessment and restoration measures aimed at stabilizing forest and aquatic ecosystems. The analysis demonstrates that current changes in forest distribution result from the combined effects of climatic variability and persistent anthropogenic pressure.

Introduction

According to the Forest Code of the Republic of Armenia adopted in 2005, a forest is defined as *"an interconnected and interacting unity of biodiversity and natural environment components, dominated by tree and shrub vegetation on forest lands or other lands allocated for afforestation, with a minimum area of 0.1 hectares, a minimum width of 10 meters, and a canopy cover of at least 30 percent of the given area, as well as non-forested lands that were previously forest-covered forest lands"* (Forest Code of RA).

Forests are foundational to Earth's life-support systems and human well-being. ScienceDirect-indexed research demonstrates that forests regulate climate through carbon storage and sequestration, cool land surfaces via water–energy cycling, sustain biodiversity that underpins ecosystem functioning, secure freshwater services through hydrological regulation, reduce disaster risks, and contribute directly to livelihoods, food systems, and public health [1]. A forest is not only a source of timber but also provides numerous non-timber products and essential ecosystem services, including climate regulation, soil protection, and water retention. At the same time, the aesthetic, recreational and health values of trees and shrubs are also significant [2]. Simultaneously, Forests contribute to biodiversity conservation, regulation of the water cycle, and the promotion of human well-being by providing recreational, cultural, and health-related services [3, 4, 5, 6, 7].

Forest ecosystem multifunctionality, the capacity of forests to simultaneously deliver multiple ecosystem functions and services, is being increasingly affected by pressures stemming from anthropogenic activities and climate change [8]. In this context, forest condition cannot be assessed exclusively through changes in total forest area. Forest composition, structural diversity, spatial connectivity, regeneration capacity and the continuity of ecological processes are also essential indicators of ecosystem integrity. A reduction in these attributes may weaken the capacity of forests to provide several ecosystem services simultaneously, even where nominal forest cover remains relatively stable [9]. Climate change has a strong impact on forests, enhancing their growth but also posing risks to them. Conversely, forests can mitigate climate change, as they have a considerable impact on global surface temperatures through their influence on the land–atmosphere energy exchange and the absorption of vast amounts of CO_2 through photosynthesis [10]. The carbon cycle of forest ecosystems plays an important role in cutting down global environmental pressure, reducing greenhouse effects, and assimilating carbon dioxide [11]. The relationship between forests and climate change is therefore bidirectional. Forests contribute to climate regulation, but climatic warming, increasing evaporative demand, drought, pest outbreaks and altered disturbance regimes may reduce forest productivity and increase tree mortality. These pressures are particularly important in high-mountain and semi-arid environments, where forest regeneration is strongly constrained by temperature, soil moisture and short growing seasons [12]. Under these circumstances, analyzing the spatio-temporal dynamics of forest cover becomes essential for identifying the main trends, vulnerable areas, and combined impacts of climatic and anthropogenic factors. The results of such analyses can inform strategies for sustainable forest management and long-term conservation of the Lake Sevan basin ecosystem.

At present, forest lands in Armenia cover approximately 344.2 thousand hectares, of which 277.1 thousand hectares are forested. Within the Lake Sevan basin, forested territories include recreational zones and the Sevan National Park [13].

Forests perform a wide range of ecological functions, such as climate regulation, water conservation, erosion control and maintenance of mineral balance in the lake ecosystem [14]. I suggest: They stabilize slopes, strengthen the soil through their root systems, reduce surface runoff, and prevent both sheet and gully erosion. [15]. Among these, the water-regulating function of forests is of particular importance [16].

Forested catchments reduce surface runoff and enhance groundwater recharge, resulting in more stable river flow regimes with smaller seasonal fluctuations. When shrub or meadow vegetation is replaced by forest vegetation, the amount of water absorbed and stored water in the basin increases by 2.38 times [17]. Thus, afforestation alone can significantly enhance local water storage capacity without additional hydraulic infrastructure.

From a landscape perspective, the ecological significance of Lake Sevan's forests extends beyond the boundaries of individual forest stands. Their location within river catchments, steep slopes, shoreline zones and ecological corridors determines their contribution to erosion control, water regulation, habitat connectivity and the reduction of sediment and nutrient inputs into the lake. Consequently, forest degradation may generate cumulative effects throughout the basin and intensify existing pressures on the aquatic ecosystem.

The study aims to analyze and assess the patterns of anthropogenic change in the forest landscapes of the Lake Sevan basin, particularly under the current conditions of climate change. Lake Sevan is the largest freshwater system in Armenia, whose ecosystem stability largely depends on the balance and sustainable use of the basin's natural resources. In this context, forested areas play a key role in reducing soil erosion, regulating the hydrological regime, preserving biodiversity, and maintaining local climate stability.

In recent decades, climatic fluctuations and human activities have caused a noticeable reduction in forest cover and changes in its spatial distribution. These alterations disrupt the ecological equilibrium of the basin, increasing the risks to water resources, biodiversity, and soil stability.

This study provides the first comprehensive assessment of anthropogenic transformations in the forested areas of the Lake Sevan basin and their potential link to ongoing climate change. As a result, the main trends in forest cover dynamics have been identified, together with the area most vulnerable to climatic fluctuations and the associated ecological risks. The study also interprets these changes through the concepts of ecosystem multifunctionality, ecological resilience and integrated landscape restoration, thereby linking observed forest dynamics with their broader implications for basin-scale sustainability [8, 9].

During the last two centuries, social perception of forest roles has suffered deep changes. New environmental roles, i.e. CO_2 storage and biodiversity, have been added to erosion control and watershed regulation [18]. The trend of anthropogenic change of forests is observed almost on whole territory of Caucasus eco-region, especially in plain areas. Therefore, the decreasing trend of forest area, phytomass amount, also the ecological functions are evident [19]. The Caucasus Ecoregion is rich in forests. The total area of forests covers 18.52 % of the total land area of the Ecoregion and it is considered as the most important for biodiversity conservation [20]. The findings reveal substantial forest decline over the past three decades, accompanied by rapid expansion of agricultural land, settlements, and degraded areas [21]. Improved land use planning, enhanced inter-sectoral coordination, upscaling of participatory forest management particularly in village forests, enhanced performance of institutions mandated to manage forest resources and taking advantages of climate finance opportunities are recommended as means of achieving emission reduction and sustaining the role of forests as carbon sinks [22].

Study area. The Lake Sevan basin, located in the central-eastern part of Armenia, occupies approximately one-sixth of the country's total territory. The lake is surrounded by mountain ranges rising 500 to 1,800 meters above the lake level. The Lake Sevan basin is surrounded by Geghama Mountains (from West), Vardenis Mountains (from South), Areguni Mountains (North-East) and Sevan and East Sevan (East) mountain ranges with elevations up to 3598 m (Vardenis). One of the peculiarities of Lake Sevan basin is the small ratio between the catchment area and the surface area of the Lake (3:1) compared to other major lakes (10:1 in average).

The climate of the basin is temperate continental, characterized by cold winters, relatively warm and sunny summers, and humid, variable conditions during spring and autumn [23]. The Lake Sevan basin is one of the sparsely forested regions of the Republic of Armenia; the current forest cover (12.5 thousand ha) is only 3% of the total forest cover of the republic [24, 25]. Natural forests occupy approximately 3.0 thousand ha, mainly concentrated on the steep slopes of the Areguni and Sevan Mountain ranges where oak (*Quercus spp.*) and juniper (*Juniperus spp.*) communities dominate [26, 27].

The flora of the basin is typical to the highlands of the Transcaucasus Region known with great diversity of plants. Along the shoreline of the lake the greatest artificial woodland of the country is situated, which offers various examples of natural and human affected ecological successions. Aquatic associations (plankton, benthos, ichthyofauna) are qualitatively poor with only a few dominant species, which has simplified studies on ecological relationships (food web, etc.) [28].

The degree of forestation of river basins is very insignificant: in the Pambak and Daranak river

Table 1

Main characteristics of the river catchments in the Lake Sevan basin

River - point	Main characteristics of the river catchments			
	average height, m	average slope, ‰	forest cover, %	plowing, %
r. Dzknaget – p. Tsovagyugh	2220	211	–	15
r. Drakhtik –p. Drakhtik	2270	246	–	35
r. Pambak – p. Pambak	2540	433	15	–
r. Daranak – p. Daranak	2530	341	31	–
r. Masrik – p. Tsovak	2310	158	1	20
r. Karchaghbyur – p, Karchaghbyur	2650	174	–	15
r. Artsvanist – p. Artsvanist	2540	192	–	25
r. Vadenis – p. Vardenik	2680	279	–	25
r. Martuni – p. Geghhovit	2760	285	–	15
r. Argichi – p. Getashen	2470	144	–	10
r. Tsaghkashen – p. Vaghashen	2570	–	–	–
r. Lichk – p. Lichk	2060	87	–	50
r. Bakhtak – p. Tsakqar	2570	123	–	15
r. Shoghvak – p. Dzoragyugh	2650	170	–	35
r. Gavaraget – p. Noratus	2430	133	<1	15

basins it does not exceed 31%, and in the Masrik and Gavaraget river basins it is 1% (Table 1). The average height is from 1900 to 2300 m. The average slope of the river from the remote point is from 87 to 433‰.

Water abstraction and allocation in the Lake Sevan basin is carried out for drinking-household, irrigation, industrial, hydropower generation, fish-farming and watering purposes.

Material and methods

The research was based on a combination of field observations, spatial analysis, and a review of published [29, 30, 31, 32] and institutional data sources. Relevant literature and cartographic materials were analyzed, including works by Khanjyan [13], Vardanyan [26], Grigoryan [27], Olchev et al. [33] and Margaryan et al. [34].

In accordance with the objectives of the study, a geographical–comparative approach was applied, integrating map interpretation, statistical analysis, and semi-stationary field observations. The research involved the comparison of historical and contemporary forest maps, the evaluation of forest cover dynamics, and the identification of areas most affected by anthropogenic pressure. Quantitative assessments were complemented by qualitative field inspections, which allowed for the verification of remote and cartographic data in situ.

Additional information was obtained from the State Committee for Forestry, the Cadastre Committee, and the Ministry of Environment of the Republic of Armenia, as well as from the Gegharkunik Regional Administration. These datasets included official statistics, forest management plans, and legal documents regulating forest use and protection within the Lake Sevan basin. Reports and guidelines from international environmental organizations were also examined to provide a broader contextual framework for assessing forest dynamics under climate change.

Furthermore, international and national policy frameworks were reviewed to ensure that the study aligns with current forest management and restoration strategies. These included the FAO State of the World's Forests [35], the IPCC Sixth Assessment Report [36], the UNECE/FAO Regional Analysis on Forest Landscape Restoration in the Caucasus and Central Asia [37], the UNEP Frontiers Report [38], and the National Forest Program of Armenia 2021–2030 [39]. Together, these references offer a comparative perspective that situates the Lake Sevan basin within the broader context of global forest change and restoration policies.

The interpretation of the results followed a landscape-based analytical framework. The observed changes were considered in relation to five interconnected dimensions: forest extent, forest origin and composition, spatial location within the basin, exposure to climatic and anthropogenic pressures, and capacity to maintain ecosystem services. This framework made it possible to distinguish between simple changes in forest area and broader processes of forest landscape degradation [8, 9, 40].

Table 2

Main agroclimatic indicators of Gegharkunik region by altitudinal zones [43]

Climatic indicators		Altitude above sea level (m)				
		1800	2000	2200	2500	3000
Average air Temperature, C°	July	17-19	14-16	13-15	11-13	9-10
	absolute maximum	33-35	31-33	29-30	26-29	22-25
	absolute minimum	-32 – -39	-32 – -41	-32 – -42		
	annual sum of days above 10 C°	1900-2300	1500-1900	1200-1500	900-1100	300
	Number of days above 10 C°	140-155	110-140	100-120	70-90	25-35
	Number of days above 5 C°	195-205	175-190	165-180	145-155	95-105
Frost-free period on the soil surface	Beginning	26/05	05/06	15/06	25/06	
	End	29/09	18/09	05/09	24/08	
	duration	126	105	82	60	
Number of precipitations, mm	annual	600-650	450-500	550-600	650-750	800-900
	growing season	400-450	300-350	350-400	400-450	500-550
Annual evaporation deficit, mm		500	450	400	300	250
Humidification coefficient		0,25-0,45	0,35-0,55	0,45-0,70	0,75-0,95	
Maximum number of days with snow, days		30-35	15-35	10-20		
Number of days with stable snow cover, days		94-111	94-112	118-135	160-165	207-216
Effective moisture reserves in the 0-50 cm soil layer, mm	during autumn sowing	50-60	50-75			
	during spring sowing	33-90	100-110			

However, the study does not provide a statistical attribution of forest-cover change to individual climatic and anthropogenic drivers. The relationships identified should therefore be interpreted as spatially and historically supported associations rather than as direct causal estimates.

Results and Discussion

The formation and distribution of forest landscapes in the Lake Sevan basin are closely linked to the specific climatic conditions of the region (table 2).

Studies indicate a clear warming trend, with a gradual increase in mean annual air temperature [41, 42]. This trend has significant implications for forest productivity, spatial distribution and future reforestation strategies. However, the effects of warming should be interpreted together with precipitation variability, soil moisture, slope exposure, altitude and forest composition. Higher temperatures may extend the growing season at some elevations, but they may also increase evapotranspiration and water stress, particularly in the lower and drier parts of the basin. Consequently, climatic warming may produce contrasting effects depending on local environmental conditions and the ecological requirements of individual tree species [10, 36]. The basin receives between 400 and 450 mm of precipitation during the growing season and between 800 and 900 mm annually. The humidity coefficient varies from 0.25 to 0.95, while the annual evaporation deficit ranges from 250 to 500 mm.

Research shows that forest landscapes have little or no influence on regional ice conditions [44].

Historically, forest cover in the basin was much greater, as demonstrated by archaeological, pollen, and palaeoecological evidence [31, 32]. During different historical periods, the coastal zones of Lake Sevan were densely populated, and deforestation was mainly driven by anthropogenic pressure. Similar long-term reductions in forest cover have also been recorded in other parts of Armenia, such as the Tavush region, where continuous human impact combined with progressive climatic aridification has reduced forested area to about 51 % of its former extent [45].

These historical trajectories demonstrate that present-day forest patterns are the result of interacting social and ecological processes. Current forest vulnerability is therefore partly inherited from previous periods of intensive resource use, which reduced stand density, simplified forest structure and weakened natural regeneration. Climate change may act as an additional pressure on forests that are already structurally degraded and fragmented.

According to Grigoryan [2], the Sevan basin is considered the poorest in terms of forest mass (Fig. 1). The eastern oak (*Quercus spp.*) is the



Fig. 1. Forested areas in the Lake Sevan basin (current situation) [14, 32]

most widespread species, valued for its durable and high-quality wood. Caucasian pine (Pinus caucasica) predominates in the low-growing forests on the former lakebed and is widely used in green-construction projects. Other species, such as broad-leaved maple (*Acer platanoides*), birch (Betula spp.), and elliptic-leaved willow (*Salix spp.*) are also present, although some provide low-value timber with limited industrial use.

The forests of the Lake Sevan basin are currently under strong anthropogenic pressure, including recreational overuse, grazing, and unregulated logging, which have severely degraded the forest fund of the Sevan National Park [**25, 31**]. Table 3 presents the number of tree and shrub species in Armenia and within the Sevan basin [**2**], confirming its comparatively low floristic diversity.

The cumulative character of these pressures is particularly relevant. Grazing can limit seedling establishment, logging can simplify stand structure, recreational use can compact soils, and fragmentation can reduce ecological connectivity. When these processes occur simultaneously, they may lower forest resilience and increase the time required for natural recovery following drought, pest outbreaks or other disturbances [46].

Widespread illegal logging peaked during the 1990s, particularly in the Martuni and Gavar sectors of the national park, where about 500 hectares of forest were lost. This uncontrolled exploitation significantly reduced stand density and hindered the natural regeneration capacity of forest ecosystems.

In addition, the forests are increasingly affected by insect pests, mainly belonging to the class Insecta (arthropods), which attack roots, leaves, fruits, and seeds. In recent years, extensive pine dieback has been observed, causing the drying of large forest tracts. Since aerial chemical control measures have proven ineffective and ecologically harmful, alternative restoration strategies are recommended.

Restoration planning should not be based solely on the identification of fast-growing or drought-tolerant species. It should also consider ecological suitability, provenance, genetic diversity, potential invasiveness, compatibility

Table 3

Number of tree and shrub species in Armenia by forest massif [2]

Forests	Number of species	Including			From whom		
		trees	shrubs	wraps	evergreens	conifers	deciduous species
Sevan Basin	82	26	56	–	2	5	75
Armenia	262	110	146	6	6	7	249

with local habitats and the future climatic conditions expected at different elevations and slope exposures. Priority should be given to native species and to the reinforcement of natural regeneration wherever ecological conditions make this possible [12].

We propose the use of more climate-resilient tree species in new afforestation programs, such as poplar (Populus deltoides), ash (Fraxinus excelsior), birch (Betula spp.), and high-mountain maple (Acer ibericum); and among shrubs, viburnum (Viburnum lantana), currant (Ribes orientalis), gooseberry (Ribes uva-crispa), and Caucasian honeysuckle (Lonicera iberica). Special attention should be given to the restoration of native juniper (Juniperus polycarpos) and oak (Quercus macranthera) forests, which formerly dominated the slopes of the Sevan range. Junipers prefer arid, south-facing slopes, whereas oaks thrive on the moister, north-facing ones. In many places, former oak forests have degenerated into shrublands, with 6–9 shoots emerging from a single stump as a result of intensive felling during the 1990s. Implementing stump-shoot thinning and selective restoration [**47**] could help recover a healthy forest structure. The main part of the activities carried out to combat forest diseases and damage falls on aerial chemical control, which in many cases is destructive for the existence of some forest animal species.

A diversified restoration strategy would increase structural and functional heterogeneity and reduce dependence on uniform plantations. Mixed stands containing species with complementary ecological traits are generally better positioned to maintain multiple ecosystem functions under changing environmental conditions than simplified, even-aged plantations. Restoration should therefore combine assisted natural regeneration, selective thinning, enrichment planting and the protection of regenerating stands from excessive grazing [8, 12].

The Lake Sevan basin forests are characterized by low productivity and limited industrial importance [26]. The maximum forest cover occurred in the mid-1980s, when plantations established during the 1960s–1970s matured and were incorporated into the forest belt, reaching about 14.5 thousand ha.

Most forests in the basin are artificial plantations created after the artificial lowering of the lake level in the mid-20th century. Extensive afforestation campaigns were implemented in the 1960s on newly exposed soils [32], using mainly poplar, willow, and pine species. Additional thickets of sea buckthorn (*Hippophae rhamnoides*) and yellow acacia (*Caragana arborescens*) also developed naturally. Since 2002, a general rising trend has been observed, resulting in the flooding of coastal forest stands and significant ecological impacts. Continuous inundation has created water-logged zones, leading to tree mortality and deterioration of water quality. Consequently, since 2005, clean-up operations have been periodically conducted in submerged forest areas to mitigate these effects.

The flooding of artificial shoreline plantations illustrates a complex management trade-off. The recovery of the lake's water level can contribute to aquatic ecosystem restoration, while simultaneously causing the loss of terrestrial forest stands established on formerly exposed lakebed. These areas should therefore not be interpreted only as forest loss, but as transition zones in which aquatic restoration, water quality, dead biomass removal, shoreline habitat development and landscape connectivity need to be managed jointly [37, 40, 48].

Studies predict that if the lake level reaches 1903.5 m, approximately 4 thousand hectares of forest would be inundated, requiring additional clearing and further disrupting the ecological balance of the basin. To date, about 1.6 thousand hectares of flooded forests have already been removed. Overall, due to the combined effects of illegal logging (since the 1990s) and state-authorized clearing of flooded forests (since the mid-2000s), the total forest area of the Lake Sevan basin has declined by around 2 thousand ha compared with its maximum in the 1980s, now covering approximately 12.5 thousand ha (Fig. 1). If the state clearing program continues up to the target water level of 1903.5 m, an additional 2.4 thousand ha may be lost in the coming years, further reducing the already fragile forest ecosystem of the basin.

From a Forest Landscape Restoration perspective, the objective should not be to maximize tree cover uniformly throughout the basin. Restoration priorities should vary according to landscape position and ecological function. On steep slopes and in river catchments, priority should be given to soil protection, erosion control and hydrological regulation. In degraded natural forests, management should promote regeneration, structural complexity and native species recovery. In shoreline areas affected by rising water levels, interventions should be coordinated with aquatic restoration objectives. Around settlements and recreational zones, restoration should also incorporate social use, fire prevention, environmental education and community participation [37, 40].

This differentiated approach would help reconcile forest conservation with water management, biodiversity protection and local development. It would also strengthen the capacity of the Lake Sevan landscape to absorb disturbance, reorganize and continue delivering

essential ecosystem services under future climatic and socioeconomic change [9, 46].

Conclusion

The study of the spatio-temporal dynamics of forest cover in the Lake Sevan basin demonstrates that changes in forest distribution result from the combined effects of climatic variability and long-term anthropogenic pressure. The identified patterns reveal significant spatial heterogeneity, with particularly vulnerable zones located along the steep slopes and coastal areas of the basin. These findings highlight the critical role of forests in maintaining ecosystem stability, supporting soil protection, water regulation, and biodiversity conservation in this fragile high-mountain environment. Over the past decades, deforestation driven by unregulated and illegal logging, as well as by the clearance of flooded forests, has led to a substantial reduction in forested area. However, forest degradation in the basin involves more than a decline in total area. It also includes the simplification of stand structure, limited natural regeneration, fragmentation, declining connectivity and the weakening of ecosystem functions.

To prevent further degradation and restore the ecological balance of the basin–especially under current climate change conditions–integrated restoration programs should be implemented [12, 37]. These programs should combine reforestation with native and climate-adapted species, continuous monitoring, and community-based participation and environmental education. Restoration should be planned at the landscape scale and adapted to the ecological functions of different parts of the basin rather than applying a uniform afforestation model [37, 40]. It is recommended that new forest plantations prioritize poplar (*Populus deltoides*), ash (*Fraxinus excelsior*), birch (Betula spp.), and high-mountain maple (Acer ibericum), while shrub species such as viburnum (*Viburnum lantana*), currant (*Ribes orientalis*), and Caucasian honeysuckle (*Lonicera iberica*) can enhance structural diversity and ecological resilience. In addition, stump-shoot restoration in degraded oak stands (*Quercus macranthera*) on the northern slopes of the Sevan range is essential to re-establish a healthy and self-sustaining forest structure. Nevertheless, species selection should be preceded by site-specific assessment and should prioritize native provenance, ecological compatibility and genetic diversity. Assisted natural regeneration should be preferred where viable, while planting should be concentrated in areas where natural recovery is unlikely [12].

The current forestry management system in the Lake Sevan basin requires substantial institutional and financial reform. Limited state funding forces management bodies to focus on short-term exploitation rather than on long-term forest recovery. A transition towards sustainable, ecosystem-based forest management, in accordance with the Forest Code of Armenia and international restoration principles [12, 35, 37], is therefore urgently needed. Such a transition requires coordination between forestry, water management, protected-area administration, agriculture and local authorities, because the main pressures and ecological effects extend across sectoral and administrative boundaries.

Finally, forest conservation and restoration should be recognized as a national and regional priority, aligned with Armenia's commitments under global environmental frameworks. Strengthening forest resilience in the Lake Sevan basin would not only protect forest resources but also contribute to water security, erosion control, biodiversity conservation and adaptation to climate change [9, 46, 48]. The basin could therefore become a model for integrated Forest Landscape Restoration in other mountain regions of the South Caucasus [37, 40].

Фінансування: Дослідження було проведено за фінансової підтримки Наукового комітету Республіки Вірменія в рамках наукового проєкту 24WS-1E035.

Funding: The study was carried out with the financial support of the Science Committee of the Republic of Armenia within the framework of scientific project 24WS-1E035.

Внесок авторів: всі автори зробили рівний внесок у цю роботу
Конфлікт інтересів: автори повідомляють про відсутність конфлікту інтересів
Декларація про використання генеративного штучного інтелекту: автори підтверджують, що під час підготовки рукопису не використовувалися інструменти штучного інтелекту.

Authors Contribution: All authors have contributed equally to this work
Conflict of Interest: The authors declare no conflict of interest

Declaration of use of generative artificial intelligence: The authors confirm that no AI tools were used during the preparation of the manuscript.

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АНОТАЦІЯ

У статті аналізується просторово-часова динаміка лісових ландшафтів у басейні озера Севан. Цей район є одним із найменш заліснених регіонів Вірменії; його ліси характеризуються низькою продуктивністю та обмеженим промисловим значенням. Значна частина лісів (12,5 тис. га) має штучне походження, тоді як природні ліси (близько 3,0 тис. га) зосереджені переважно на крутих схилах хребтів Арегуні та Севан, де переважають дубові та ялівцеві угруповання. Ліси регулюють клімат шляхом накопичення та секвестрації вуглецю, підтримують біорізноманіття, забезпечують гідрологічне регулювання, стабільність ґрунтів, зменшують ризики природних небезпек і сприяють добробуту населення. У басейні озера Севан деградація лісів впливає не лише на деревний покрив, а й на гідрологічне регулювання, стабільність ґрунтів, екологічні зв›язки, біорізноманіття та екологічний стан озера. Мета дослідження – проаналізувати та оцінити закономірності антропогенних змін у лісових ландшафтах басейну озера Севан в умовах сучасної зміни клімату. Об›єктом дослідження є лісові ландшафти басейну озера Севан, предметом – динаміка лісового покриву та пов'язані з нею екологічні ризики. Дослідження базувалося на поєднанні польових спостережень, просторового аналізу та опрацювання опублікованих і відомчих джерел. Застосовано географічно-порівняльний підхід, що поєднав картографічний і статистичний аналіз, порівняння історичних та сучасних лісових карт, оцінку динаміки лісового покриву й визначення територій, найбільш уражених антропогенним тиском. Польові обстеження дали змогу перевірити результати дистанційних і картографічних досліджень. Додаткові дані отримано від Державного комітету лісового господарства, Кадастрового комітету, Міністерства навколишнього середовища Республіки Вірменія, Гегаркунікської регіональної адміністрації та міжнародних екологічних організацій. Встановлено, що історично рівень заліснення регіону був значно вищим, однак істотно знизився під впливом тривалого антропогенного тиску. Вирубування лісів триває через незаконні та нерегульовані рубки, а також втрату затоплених лісових ділянок унаслідок коливань рівня води в озері. Ці процеси загрожують екологічній рівновазі басейну та підтверджують, що сучасні зміни у розподілі лісів є результатом поєднаного впливу кліматичної мінливості й довготривалого антропогенного навантаження, що потребує комплексних заходів із відновлення та збереження лісових і водних екосистем.

ІНФОРМАЦІЯ ПРО СТАТТЮ :

Рукопис надійшов
23 жовтня 2025

Отримано після рецензування
7 квітня 2026

Затверджено до друку
25 травня 2026

Опубліковано онлайн
30 травня 2026

Ключові слова:

Вірменія, басейн озера Севан, динаміка лісу, просторово-часові моделі, антропогенні зміни, льодові явища, вирубка лісів, екологічний баланс, відновлення лісового ландшафту, екосистемні послуги, екологічна стійкість.

https://doi.org/10.26565/2410-7360-2026-64-17

UDC: 551.509.324

Impacts of regional climate change on hazardous hydrometeorological events in Azerbaijan

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ABSTRACT

Problem definition. Currently observed climate change on Earth is exerting its impacts across all regions. Contemporary warming is manifested more prominently in the mid-latitudes. Over time, changes in the spatiotemporal recurrence of hazardous hydrometeorological events necessitate continuous monitoring of the current state of hydrometeorological elements.
Formulation of the purpose. The article is devoted to the impacts of global climate change on regional climate change in Azerbaijan and the hazardous hydrometeorological events it generates, with particular emphasis on river water resources. Global climate change on Earth is briefly analyzed, and its regional impacts on the territory of Azerbaijan are investigated based on a comparative analysis of recent and long-term historical observational data.
Research methods. In the study, annual indicators of climatic elements were obtained using mathematical and statistical methods. To monitor recent changes, a comparative analysis was conducted between standard climatic values (1961–1990) and corresponding indicators from shorter time periods.
The main material. The study utilizes observational data collected from 61 active meteorological and 84 hydrological stations of the National Hydrometeorology Service operating on the territory of the Republic of Azerbaijan. The dataset covers the period 1961–2025 and includes measurements of various hydrometeorological elements.
Conclusions. The analysis shows that, relative to the long-term climatic norm (1961–1990), the mean annual temperature increase in the country was 1.1°C for the period 1991–2025, while it reached 1.3°C for 2007–2025. However, in 2025 alone, this increase amounted to 1.8°C. For the indicated periods, a continuous decline is observed in both annual precipitation amounts and river discharge. Significant changes in river flow regimes are taking place, including a decrease in discharge volumes during spring–autumn flood and high-water periods, and an increase during low-water winter periods. The dynamics of hazardous hydrometeorological processes causing natural disasters in the country are intensifying in connection with regional climate change. At the same time, it is emphasized that the obtained empirical results should be utilized by the scientific community and taken into account in various applied and planning projects.

ARTICLE INFO

Manuscript received
29 March 2026

Revised manuscript received
8 May 2026

Manuscript accepted
25 May 2026

Available online
30 May 2026

Keywords:

Climate change, air temperature, atmospheric precipitation, river discharge, water resources, hail, snow avalanches, extreme hydrometeorological parameters, flood events, Azerbaijan.

Introduction

Currently, two major natural problems are observed on Earth: the first is atmospheric warming, and the second is the water-related crisis [1, 3], including water scarcity and other hazardous hydrometeorological events arising under the influence of climate change [29].

In the contemporary period, one of the most critical issues concerning the global population [11], state and scientific communities, and international organizations is global climate change and the increasing negative impacts it exerts on the environment, particularly on the world's water bodies [21]. Climate change and the resulting economic damages to water resources [15], populations [3], biodiversity, agriculture, and infrastructure sectors, as well as the natural disasters it generates, represent one of the most significant natural challenges facing humanity [11, 28].

In cites: Mahmudov Rza (2026). Impacts of regional climate change on hazardous hydrometeorological events in Azerbaijan. *Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology*, (64), 216–227. https://doi.org/10.26565/2410-7360-2026-64-17



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Climate change also leads to fluctuations in sea levels, desertification, an increase in forest fires, regime changes in surface and groundwater resources, and a reduction in snow, ice, and freshwater reserves [2, 4, 24 25]. In addition, it contributes to the emergence of problems in human lifestyle and health, thereby posing a wide range of challenges that must be addressed by the global community [16, 23].

According to data from the World Meteorological Organization, 80–85% of natural disasters occurring worldwide are associated with hydrometeorological processes, and 20 of the last 22 years have been classified as warm years characterized by persistent temperature increases [30]. The period 2006-2025 represents the warmest interval of the last 1,500 years, with high temperature values recorded in most regions of the world [10, 14]. Record high temperatures have also been accompanied by an increase in the dynamics of hazardous hydrometeorological events in many regions of Azerbaijan [20, 25].

At the regional scale, these problems manifest at different levels and, naturally, are more clearly expressed in Azerbaijan, which has a distinct physical-geographical and hydrometeorological setting. This is particularly evident in the long-term regime of the country's climate and water bodies, as well as in the occurrence of extreme precipitation, floods, mudflows, hail, droughts, forest fires, and other hazardous hydrometeorological events [5, 14].

Climate is a complex system, and the causes of its change are associated with both natural and anthropogenic factors [13, 29]. Thus, even in periods when human civilization did not exist, natural climate variations occurred on Earth. In this context, periodic changes in the Earth's orbital trajectories, variations in magnetic poles, strong volcanic eruptions, and physical processes occurring on the Sun are among the natural factors contributing to climate change [27]. At present, however, anthropogenic influences have significantly accelerated this process. The expansion of agriculture, industry, and urbanization has, in turn, affected the Earth's energy balance, leading to observable changes in the climate system [2].

The climate of the territory of Azerbaijan is also an integral part of the global climate system, and processes occurring within this system affect the country's climatic conditions with varying intensity and over different time scales [18, 26]. Therefore, the study of climate change, the assessment of its impacts on various sectors of the economy, and the investigation of adaptation capacities of the economic and production systems have become an important issue requiring urgent attention for Azerbaijan and its economy. In this regard, the United Nations Climate Change Conferences of the Parties held in Azerbaijan in 2024 and in Brazil in 2025 (COP-29 and COP-30) play a significant role in addressing these challenges [7].

Multiple impacts of climate change are already evident in the territory of the Republic of Azerbaijan. Previously, studies conducted by N.Sh.Huseynov, F.A.Imanov, R.N.Mahmudov, S.H.Safarov, A.S.Mammadov, J.S.Huseynov, and other researchers focused on climate-forming factors such as atmospheric precipitation, air temperature, snow cover, drought, and related variables in Azerbaijan. However, earlier studies did not investigate the impacts of climate change on individual hydrometeorological processes in recent years. Therefore, this study examines the recent impacts of climate change on hydrometeorological processes and identifies scientifically significant results for the academic community.

The aim of the study is to assess the impacts of regional climate change on the territory of Azerbaijan and to conduct a long-term analysis of the hazardous hydrometeorological events it generates.

Materials and methods

The methodology of the study is based on the comparative spatiotemporal analysis of long-term hydrometeorological observational data. Some calculations rely on statistical analysis, geographical interpolation, and specific empirical formulas. The data base of the study consists of long-term observational records from approximately 61 conventional and automatic meteorological stations and 85 hydrological sites operating in the territory of Azerbaijan, covering the period 1961-2025. In the methodological analysis, the homogeneity of meteorological and hydrological series was tested, and their statistical parameters were determined. Such analyses ensure an appropriate physical-statistical assessment of regional climate change and the natural disasters it generates.

Descriptive statistics, linear regression analysis, and the non-parametric Mann–Kendall trend test were applied to analyze hydrological and climatic time series in the study. Descriptive analysis was used to evaluate variability through the mean value, standard deviation, and coefficient of variation. To assess trends, the parametric linear regression model (formul 1) was applied, and the trend coefficient and coefficient of determination were calculated. The statistical significance of the trend was tested based on the t-test. In addition, non-parametric trend analysis was performed using the Mann-Kendall test,

which is independent of the normality of data distribution. This approach made it possible to evaluate both the linear rate of change and the reliability of monotonic trends in hydrological and climatic data.

During the study, the linear model presented in Formula 1 was used to evaluate the temporal trend:

$$y=a+bx \quad (1)$$

Here, *x* represents the independent variable, *b* denotes the direction and rate of the trend, and a is the constant term. In this model, *y* represents the hydrological or meteorological variable (temperature, precipitation, or runoff), *x* denotes time (year), a represents the intercept, and b expresses the trend coefficient (slope).

In this process, the mean values of hydrometeorological parameters were calculated based on Formula 2:

$$\bar{x} = \sum_{i=1}^{n} x_i \quad (2)$$

Here, $\bar{x}$ denotes the mean value, (x_i) represents the i-th observation, and (n) is the number of observations. The standard deviation was calculated based on Formula 3.

$$\sigma=\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i-\bar{x})^2} \quad (3)$$

Here, σ -denotes the standard deviation, (x_i) represents the *i*-th observation, $\bar{x}$) -is the mean value, and (n) is the number of observations.

In the study, Formula 4 was used for calculating the coefficient of variation.

$$CV=\frac{\sigma}{\bar{x}}*100 \quad (4)$$

Here, *CV* denotes the coefficient of variation (%), (σ) is the standard deviation, and ($\bar{x}$) represents the mean value. The coefficient of determination was calculated using Formula 5.

$$R^2=1-\frac{\sum(y_i-\hat{y}_i)^2}{\sum(y_i-\bar{y}_i)^2} \quad (5)$$

Here, (R^2) denotes the coefficient of determination, (y_i) represents the observed (actual) values, ($\hat{y}$) represents the model-fitted values, and ($\bar{y}_i$) denotes the mean value.

To assess the statistical significance of the trend, the Mann-Kendall test was applied. In the study, Formulas 6-9 were used to calculate the S statistic, the sign function, the variance, and the Z statistic.

$$S=\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} sgn(x_j-x_i) \quad (6)$$

$$sgn(\theta)=\begin{cases}+1, & \theta>0\\ 0, & \theta=0\\ -1, & \theta<0\end{cases} \quad (7)$$

$$Var(S)=\frac{n(n-1)(2n+5)}{18} \quad (8)$$

$$Z=\begin{cases}\frac{S-1}{\sqrt{Var(S)}}, & S>0\\ 0, & S=0\\ \frac{S-1}{\sqrt{Var(S)}}, & S<0\end{cases} \quad (9)$$

In the above formulas, (x_i) denotes the observation for the i-th year, (n) represents the number of observations, ($\bar{x}_i$) is the mean value, (S) is the Mann-Kendall statistic, and (Z) denotes the standardized test statistic [6, 12].

Discussion

1.1. Changes in Temperature and Precipitation. In Azerbaijan, the mean multi-year air temperature for the period 1991-2025 increased by +1.1°C relative to the long-term climatic norm (1961–1990), while for the period 2007–2025 it increased by +1.3°C.

In the study, both parametric and non-parametric trend analyses indicated a statistically significant increase in mean annual air temperature in Azerbaijan during 2007-2025. Based on linear regression analysis, the rate of temperature increase was 0.0867°C per year (≈ 0.87°C/ 10year, $p < 0.001$). The coefficient of determination ($R^2 = 0.646$) shows that a substantial portion of temperature variability is explained by the time factor. The Mann-Kendall test also confirmed the presence of a positive trend with high statistical significance ($Z = 3.80$; $p < 0.001$). These results demonstrate a persistent regional warming process observed in Azerbaijan over the last two decades.

In the globally recognized warmest years-2018, 2023, and 2025 the mean annual air temperature in the country increased by +2.0°C, +2.2°C, and +1.8°C, respectively. Figure 1 presents the trend of mean multi-year air temperature in the territory of Azerbaijan for the period 2007-2025.

As shown in Figure 1, during this period a general increasing trend in air temperature is observed across the territory of the country. The only exception is 2011, when no increase in mean annual temperature was recorded. Table 1 presents the changes in mean multi-year temperature across different altitude intervals for the periods 2007–2025 and 2025. As can be seen from Table 1, the increase in mean multi-year temperature relative to the climatic norm is +1.0°C in the ≤0 m altitude zone. The highest temperature increase (+1.5°C) is observed in the 1–200 m and >1000 m elevation intervals. However, in 2025 the mean annual temperature increase reached +1.8°C. In this year, the

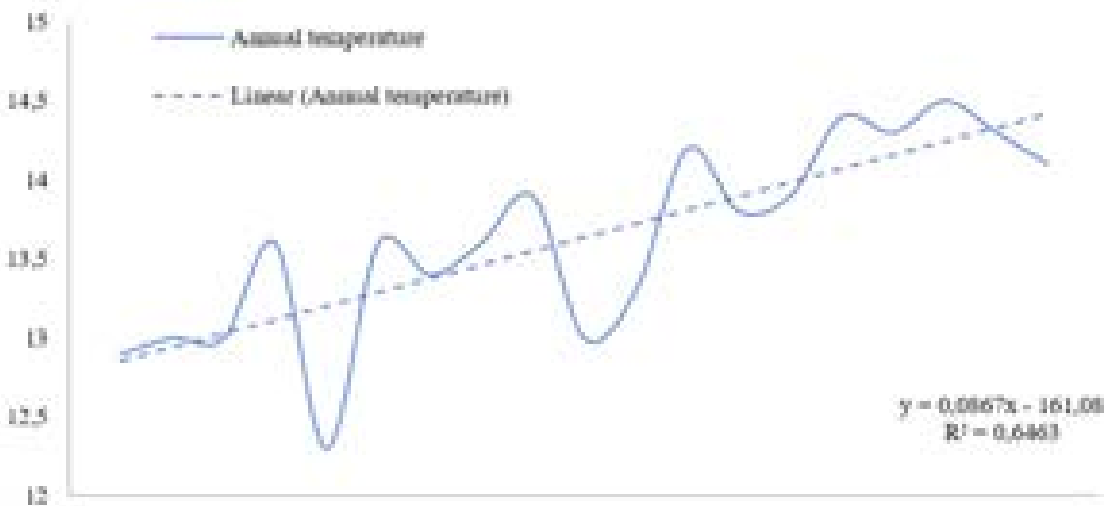


Fig. 1. Trend of mean annual air temperature in the territory of Azerbaijan

maximum temperature increase (+2.1°C) was recorded in the 1–200 m elevation interval.

The analysis of seasonal temperatures in 2025 shows that, relative to the long-term climatic norm, air temperature increased by +2.1°C in winter, +2.0°C in summer, and +1.4°C in autumn, while in spring, conversely, a decrease of 0.8°C was recorded. This further confirms the results of studies conducted over the last 20 years. These studies indicate that, although mean temperature values have increased across all seasons relative to the norm, no increase is observed specifically during the spring season.

The statistical analysis of annual precipitation for the period 2007-2025 revealed an overall decreasing trend in precipitation amounts. The long-term mean precipitation was 449 mm. Based on linear regression analysis, precipitation decreased at an average rate of 6.54 mm per year, or approximately 65 mm per decade. The statistical significance of the trend was confirmed by parametric analysis ($p < 0.05$). The Mann-Kendall non-parametric test also indicated that the negative trend is statistically significant ($Z = -2.17$; $p < 0.05$). In particular, the minimum precipitation values recorded in 2021-2022 suggest an intensification of drought conditions in recent years. Overall, the results demonstrate that regional climate change has had a significant impact on the precipitation regime.

Figure 2 presents the dynamics of mean annual precipitation in the territory of Azerbaijan for the period 2007-2025. Regarding annual precipitation, a decrease of 37.0 mm has been observed compared to the long-term norm (476 mm). For the period 2007–2025, the highest increase in precipitation across the country was recorded in 2016 (+110 mm), while the maximum decrease occurred in 2017 (-101 ==mm) [19, 20, 21].

As shown in Figure 2, a decreasing trend in precipitation dynamics is observed in recent years across the territory of the country. Compared to the long-term climatic norm (476 mm), this decrease amounts to 37 mm for the period



Fig. 2. Precipitation trend in the territory of the Republic of Azerbaijan

Table 1

Changes in mean multi-year air temperature across different altitudinal intervals in the territory of Azerbaijan

Periods	Elevation intervals, m					Republic
	≤ 0	1-200	201-500	501-100	>1000	
Norm 1961-1990	14.6	14.3	13.3	11.9	7.8	12.3
2007-2025	15.6	15.8	14.6	13.1	9.3	13.6
Anomaly	+1.0	+1.5	+1.3	+1.2	+1.5	+1.3
2025	16.1	16.4	15.3	14.3	9.0	14.5
Perennial anomaly	+1.5	+2.1	+2.0	1.9	1.2	1.8

2007–2025. It is noteworthy that, although both increases and decreases in precipitation are observed in different years across various elevation intervals, a consistent decrease throughout all years is recorded only in the 200-500 m altitude range [9, 10].

Table 2 presents the main indicators of extreme hydrometeorological events observed in recent years in the territory of Azerbaijan.

As can be seen from Table 2, during the indicated period, the maximum air temperature in the country was 44.2^{0}C in 2021, and the minimum temperature was -240C (2020). The highest frequency of flood and hail events was in 2023, with 140 hail and 147 flood events.

1.2. Impact of climate change on river flows. The river water system and water resources of any country are the product of climate (Ismayilov & Suleymanov, 2024). Since most countries are located in the same river basins, changes occurring on a global and regional scale have a complex impact on the water resources of the countries of the region. 53 countries on Earth are in the same river basin, and 33 countries are countries experiencing water shortage problems, and Azerbaijan is among these countries [4, 17]. According to a recent study by the World Resources Institute, Azerbaijan is ranked 59th among 164 countries that will face a decrease in water resources by 2050 and is classified as a country with a medium-high (20-40% water stress) risk category. In the 20th century, the demand for water worldwide has increased more than 6 times. The main reasons for this include, **first**, global climate change and its impact on the world's water resources; **second**, the growth of the global population and the increasing demand for water; and **third**, the intensification of anthropogenic pressures-particularly the discharge of wastewater from industry, agriculture, and domestic use-which leads to changes in both the quantity and quality of water resources. Naturally, there are also other secondary contributing factors. As a result of these challenges, the United Nations designated the period 2018-2028 as the "Water for Sustainable Development" decade [31].

Since Azerbaijan is mainly located within the Kura-Araz river basin, particularly in the lower reaches of these transboundary rivers, the preservation of both the quantity and quality of water resources from these rivers, as well as domestic river systems, is implemented through necessary state-level measures and projects to meet the population's water demand. In this regard, the approval of the "National Strategy on Efficient Use of Water Resources" covering the period 2024-2040 can be considered an indicator of a comprehensive approach to addressing the issue. In order to implement this 16-year National Strategy, an Action Plan has been developed, encompassing measures aligned with relevant priority directions. The Strategy emphasizes

Table 2

Extreme hydrometeorological parameters in the territory of Azerbaijan

Meteorological elements	Years					
	2020	2021	2022	2023	2024	2025
Maximum temperature, (°C)	42.2	44.2	43.3	42.6	43.4	42.9
Minimum temperature, (°C)	-24.0	-20.0	-20.0	-22.9	-19.0	-22.7
Daily maximum precipitation, mm	108	144	83.0	163	274	194
Monthly maximum precipitation, mm	234	394	274	50	30	507
Maximum wind speed, m/s	38	38	40	40	40	33
Maximum height of the abdomen, sm	88	56	80	95	54	75
Number of flood events	36	41	50	147	110	31
Number of hail events	53	34	37	140	106	61

a number of key objectives aimed at eliminating the causes of water losses in the country. For example, it sets targets to expand the application of modern irrigation methods to reach 10% nationwide by 2027, increase drinking water supply coverage to 85% and irrigation water supply to 90% through the development of water supply infrastructure, promote the use of alternative water sources, and reduce losses in drinking water supply to 33% and irrigation water losses to 42% [12, 15].

In order to use Azerbaijan's water resources more efficiently under the current conditions, it is advisable to implement the following measures in accordance with the requirements of the National Water Strategy:

- Reduction of both natural losses (utilization of water accumulated in basin depressions after rainfall and snowmelt, a practice widely used in international experience) and artificial losses within river basins;
- Reassessment of water resources based on innovative technologies;
- Assessment of regional climate change and its impacts on water bodies, as well as the development of relevant scenarios;
- Assessment of potential risks related to water sources;
- Digitalization of spatial data on water sources based on satellite technology;
- Implementation of an optimal infrastructure and management model for water basins;
- Improvement of the early warning system for the timely dissemination of operational information on floods, inundations, and other natural disasters to government agencies and the public;
- Integrated management of water resources both within river basins and between basins;
- Identification and utilization of alternative water sources;
- Establishment of wastewater recycling and management systems.

Despite this, the increasing demand for water in the Republic and its relatively limited water resources make the resolution of water-related issues more urgent. These conditions, in turn, require the continuous study of water bodies and the implementation of water management policies in line with contemporary requirements.

Azerbaijan's total water resources are estimated at around 30 km³. Under the influence of contemporary climate change, the annual river runoff has decreased by 15–20%, and in some transboundary rivers even by up to 40%, making this indicator particularly lower in dry years. Currently, renewable freshwater resources amount to 26.2 billion m³. Of this, 8.5 billion m³ is formed from groundwater, 4.6 billion m³ from local river runoff, and 13.2 billion m³ from transboundary surface waters [19].

The country's water resources account for 15% of the total water resources of the South Caucasus. Per capita water availability is 8.3 times lower than in Georgia and 1.7 times lower than in Armenia. Local water resources amount to 10 km³, transboundary water resources to 20.6 km³, and groundwater resources to 8.5 km³. However, a decrease of 4.4% in groundwater resources, up to 15% in river waters, and 35-40% in transboundary river waters has been observed. The average annual discharge of the Kura River is estimated at 17 km³, of which 9-10 km³ is formed in Georgia, 5-6 km³ in Azerbaijan, 1.5 km³ in Armenia, and 3.4 km³ in the upper reaches within the territory of Türkiye. The total water resources of the Kura-Araz basin are estimated at 25.9 km³, of which 17 km³ is formed in the Kura basin and 8.9 km³ in the Araz basin. The average annual runoff of rivers directly flowing into the Caspian Sea is 1.1 km³ from the northeastern slopes of the Greater Caucasus and 1.3 km³ from the Lankaran-Astara zone. Naturally, a decreasing trend is also observed in the runoff of these rivers. In general, although the long-term average discharge of the Kura River is 450-500 m³/s, this indicator has decreased to 277 m³/s for the period 2011-2025. There are about 450 lakes in the territory of Azerbaijan with a total area of 394 km², of which only 10 lakes have an area exceeding 5 km².

Studies show that, although in some individual years an increase in floods and river discharge is observed, the flood and high-water period flow volumes as well as maximum discharges in rivers continue to decrease. A similar process is also observed in the rivers of Eastern Europe [8, 23].

Taking into account the impacts of regional climate change, trend analyses of annual river discharges (Q_m, m³/s) and maximum water discharges (Q_{max}, m³/s) were conducted based on both observed and reconstructed hydrological series for rivers located within the territory of the country. As examples, Figures 2 and 3 present the long-term variation graphs of mean annual and maximum discharges of the respective rivers.

The statistical analysis of mean annual streamflow at the Kur-Giragkasaman station for the period 1981-2025 was conducted using both parametric (linear regression) and non-parametric (Mann-Kendall) methods. The results of the parametric analysis indicated a statistically significant decreasing trend in annual streamflow (slope = −1.93 yr^{-1}, p = 0.0095). The non-parametric Mann-Kendall test confirmed the same result (Z = −2.44, p = 0.0148), indicating that the trend is robust and independent of the data distribution. Sen's slope estimate (−1.72 yr^{-1}) quantified the magnitude of the average annual decrease in streamflow.

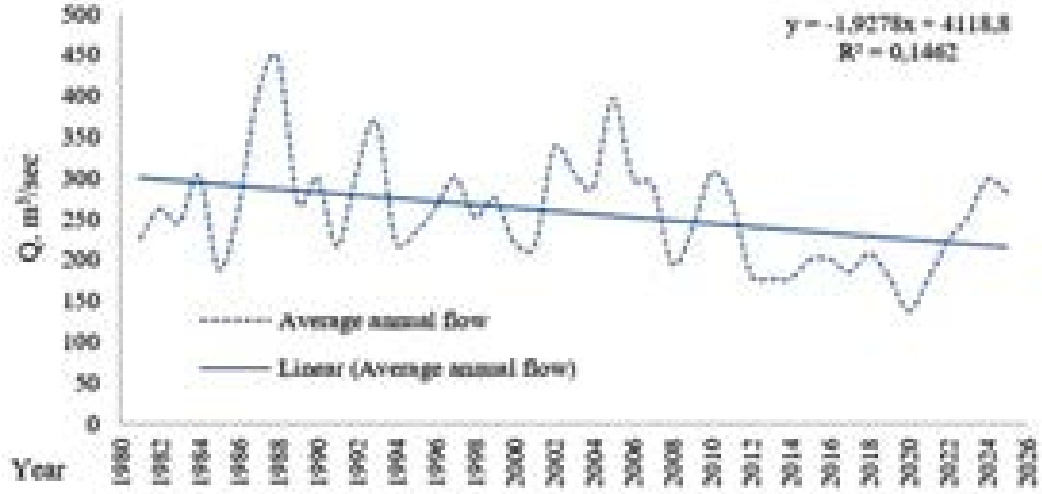


Fig. 3. Trend of average multi-year water consumption in the Kura-Giragkasaman area

Overall, the consistency of both methods demonstrates the presence of long-term hydrometeorological changes in the Kura River basin and a gradual weakening of the streamflow regime. These changes are associated with climate change, increased evaporation, and intensified anthropogenic water use.

The statistical analysis of annual maximum streamflow at the Kur-Giragkasaman station for the period 1981-2025 revealed an overall decreasing trend against a background of strong variability. The mean annual maximum discharge was 1150.2 m^3/s; however, interannual variability was high (CV=40.6%). Linear regression analysis indicated an average annual decrease of 11.66 m^3/s, while the low coefficient of determination (R^2 = 0.108) suggests that this variation is strongly influenced by stochastic components. Nevertheless, the Mann-Kendall non-parametric test confirmed that the decreasing trend is statistically significant (Z=−2.47; p = 0.013). These results indicate a weakening tendency of peak discharge in the Kura River system in recent decades and reflect ongoing changes in the hydrological regime.

As shown in Figures 3 and 4, both the long-term river discharge and the maximum flow rates of the basin rivers are decreasing under the influence of regional climate change. The observed changes in river flow regimes indicate that while discharge volumes during spring–summer flood and high-water periods are declining, winter low-water flows are, conversely, increasing. This can be explained by the fact that snow and ice water reserves, which play a key role in runoff formation, are partially converted into river discharge during the winter period due to rising average winter temperatures. As a result, a decrease in maximum discharges during flood and high-water periods is also observed.

As indicated in the National Water Strategy of the country, due to the impacts of climate change, water resources are expected to decline to 20.1 km^3 by 2040, including a reduction of surface water resources to 11.6 km^3. Consequently, the existing water deficit in the country is projected to increase from 4.0 km^3 to 8.0 km^3. Ensuring the population's and economic sectors' water supply, as well as the efficient and rational use of water

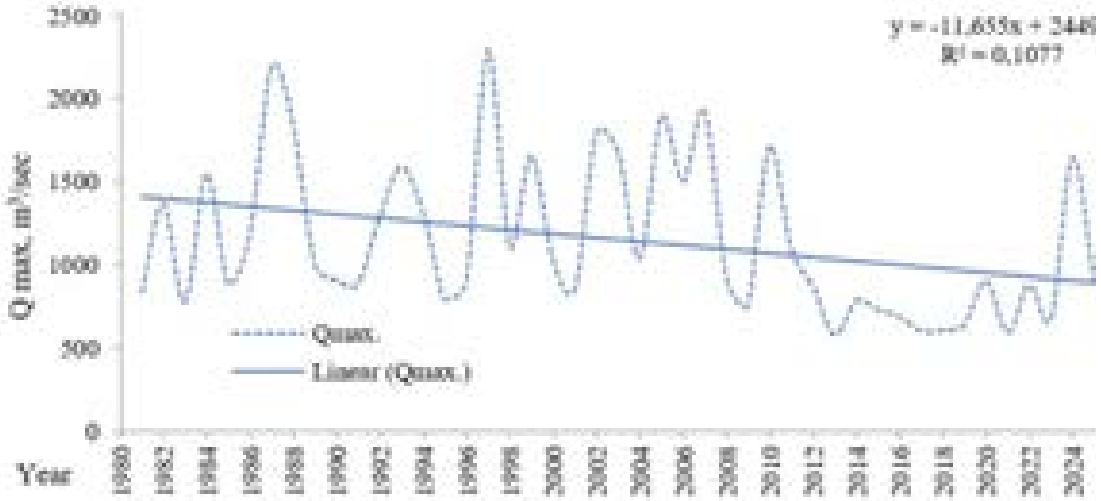


Fig. 4. Trend of maximum water consumption at the Kura-Giragkesaman point

resources, has always been one of the priority directions of Azerbaijan's water policy.

One of the water-related problems of our country is undoubtedly the fluctuation of the Caspian Sea level, more precisely its significant decline in recent years. Historically, the level of the Caspian Sea has always fluctuated with a large amplitude in response to climatic changes. Studies show that over the last 2,000 years, the sea level has varied within an amplitude of about 12 m. Over the last 300 years, this amplitude has been about 5 m, fluctuating approximately between -25 and -30 m relative to sea level. Thus, in 1882 the maximum level reached -25.2 m, while from 1929 to 1977 it decreased to -29.05 m. From 1977 to 1995, the level rose again by 2.65 m, reaching -26.04 m. Between 1995 and 2010, the sea level remained relatively stable, after which it began to decline again, reaching approximately -29.04 m by 2024 [1].

Historically, fluctuations in the Caspian Sea level have been closely linked to its water balance-comprising river inflow into the basin, evaporation from the surface, and precipitation over the basin-and to climatic changes occurring within the catchment area. Approximately 80–85% of the total annual river inflow to the Caspian Sea is contributed by the Volga River. Studies indicate that when the long-term average discharge of the Volga River is 330–350 km³/year, the sea level tends to rise; at 240–250 km³/year it remains relatively stable; and at 120–140 km³/year a declining trend is observed. A similar pattern is also reflected in other rivers flowing into the Caspian Sea. If the Caspian Sea level were to reach its historical minimum (−30 m a.s.l.), significant shoreline retreat would occur along Azerbaijan's Caspian coastal areas: approximately 4-5 km in the Nabran-Shabran zone, 10-12 km in the Sangaçal–Alat area, and 2–3 km in the Lankaran region. Such changes would create major challenges for maritime infrastructure, navigation, and the ecological environment. In addition, the merging of nearshore islands could occur, while water exchange in the Baku Bay may decrease by 3-4 times.

1.3. Flood event. The territory of Azerbaijan is considered one of the 20 countries in the world where flood hazard is most frequently observed. Flood events are mainly recorded in the Shaki-Zagatala, Nakhchivan, and high-mountain regions of the country, where both turbulent and structural types of floods occur. Numerous studies have been conducted on flood events in Azerbaijan, and the "Flood Catalogue" and "Flood Map" (2016), covering the period 1772-2025, have been published [19]. In the territory of the Republic, approximately 85% of flood events are formed due to intense rainfall, 10% due to mixed water sources, and only 5% due to snowmelt. In regional rivers, particularly in the Kish River and its tributaries, the annual sediment transport can reach 200-300 tons. The highest frequency of floods within a month occurs in both the Greater and Lesser Caucasus river systems during June and July, accounting for 31.2% and 28.0% of the annual flood discharge, respectively.

In 2020, a total of 36 flood events occurred in the territory of the country (2 in May, 2 in June, 23 in July, and 9 in August). The most hazardous events were recorded on May 10 in the Hasan Su River of the Aghstafa district, on August 2 in the Kurmuk River, and on August 15 in the Kish River.

In 2021, a total of 41 flood events were recorded (8 in May, 3 in June, 16 in July, 1 in August, 8 in September, and 5 in October). The most hazardous events occurred on June 6 in the Kish River, on July 7 in the Shamkir River, and on September 23 in the Tala, Balaken, and Katekh rivers.

In 2022, a total of 50 flood events were recorded (1 in March, 3 in April, 18 in May, 19 in June, 2 in July, 2 in August, 4 in September, and 1 in October). The most hazardous flood events were observed on May 9 in Shamakhi, on June 10 in the Ganja River, and on June 22 in Goranboy.

In 2023, a total of 147 flood events occurred (7 in April, 12 in May, 59 in June, 16 in July, 7 in August, and 46 in September). The most hazardous flood events were recorded on May 25 in the Ganja River, on June 30 in the Dashkasan district, and on August 26 in the Goychay district.

In 2024, 110 flood events were recorded in the territory of the country (12 in May, 47 in June, 43 in July, 7 in October, and 1 in November). The most hazardous floods occurred in the river basins of the Kura River, including the Gazakh, Aghstafa, and Khram tributary rivers.

In 2025, a total of 21 flood events were recorded (17 in April, 3 in May, and 1 in June). The intensity of these flood events was relatively weak.

1.4. Hail event. In Azerbaijan, hail events are observed mainly on the southern slope of the Greater Caucasus, the northern slope of the Lesser Caucasus, and in Nakhchivan. In the high mountainous areas of the Greater Caucasus (2300-2800), the number of hail events per year is 8-10 days, in the Lesser Caucasus 10-12 days, and in Nakhchivan and Karabakh 5-7 days. By month, the highest recurrence of hail in the country mainly occurs in May-June due to the increase in temperature and humidity, and the dynamics of convective processes related to orographic conditions. In recent years, the intensity and recurrence of hail events have increased due to the impact of global climate change, and sometimes large-diameter hail and ice fragments fall [20].

In 2020, 53 hail events were recorded in Azerbaijan, with an average hailstone diameter of 10-15 mm, and in some cases reaching 20-22

mm. The maximum hailstone diameter of 30 mm was observed on 15 September 2020 in the Zagatala region.

In 2021, the number of hail events was 34, with an average hailstone diameter of 8-10 mm, while the maximum diameter of 25 mm was recorded in the Dashkasan region.

In 2022, hail events were recorded over 37 days, with an average diameter of 10-12 mm and a maximum diameter of 16 mm observed in the Gadabay-Dashkasan area.

In 2023, a record 140 days of hail events were observed across different regions of the country. The highest frequency occurred in April (57 days), May (40 days), and July (43 days). The average hailstone diameter ranged between 5-15 mm, while the maximum hailstone size reached 30–35 mm in Gabala (01.06.23) and Aghdam (18.06.23). In Zagatala, hail with a diameter of 25 mm was recorded on 30.04.23 and 07.09.23.

In 2024, a total of 106 hail events were observed. The average hailstone diameter ranged from 8-14 mm, while the maximum diameter reached 30 mm, recorded in Zagatala on 07.06.24 and 18.05.24.

In 2025, 61 hail events were recorded, with an average hailstone diameter of 9–12 mm. The maximum hailstone size (24 mm) was observed on 27.06.25 in the Gadabay–Dashkasan region.

1.5. Avalanche and drought event. Avalanches caused by climatic and geomorphological factors are considered hazardous natural phenomena for the population, the economic system, the tourism sector, and other infrastructure sectors.

In the world, avalanche hazards exhibit different characteristics across various geographical regions and climatic zones. In recent years, under the influence of contemporary climate change, the dynamics of this process have continued to intensify in high-mountain areas. An avalanche occurs when the snow cover exceeds a thickness of 30-50 cm on steep slopes and moves under the influence of gravity. In some cases, the force exerted on 1 m² along its path can reach tens of tons. The average velocity of an avalanche ranges between 50-90 m/s, while in strong avalanches the flow height may reach 8-10 cm. The critical height of snow leading to avalanching depends on the internal density relationship of snow (S), the volume of snow mass (w), the internal sliding coefficient of snow (α), and the slope gradient, and can be expressed as follows: (Makhmudov et al., 2025).

$$h=\frac{S}{W\cos\alpha(\sin\alpha-tg\varphi\cos\alpha)} \qquad (10)$$

In this formula, as tgφ increases from 20° to 35-45°, the critical snow height and the probability of avalanches increase. Conversely, when the slope angle decreases, both the critical snow height and avalanche likelihood are reduced (Bračko et al., 2022).

In Azerbaijan, avalanche risk is most frequently observed in the high-mountain areas of the Greater Caucasus, Lesser Caucasus, and Nakhchivan. The author of the article has prepared an avalanche hazard map of the country's territory based on the degree of risk. The most dangerous avalanche event occurred on 16 December 2000 in the Hinal Mountain of the Lesser Caucasus physiographic region, resulting in the death of 11 military personnel. Drought events, as hazardous natural factors, are included among the most dangerous phenomena resulting from hydrometeorological processes, particularly spatial variations in climatic indicators as well as negative anthropogenic impacts. One of the main adverse consequences of drought is the intensification of desertification processes. At present, under the influence of global climate change, the dynamics of drought events continue to increase worldwide. In the territory of Azerbaijan, particularly in the arid climatic zones of the Kura-Araz Lowland, the Absheron-Gobustan area, and the Araz river valley regions, persistent drought conditions occur under the influence of regional climate change. In the districts of Ordubad, Julfa, and Babek, drought is observed for 50-70 days per year, in the Sharur-Nakhchivan area for 25–50 days, on the southern slopes of the Greater Caucasus for 15-20 days, and in the Kura-Araz Lowland for 60-80 days. Both atmospheric and soil droughts are observed in Azerbaijan. The most prolonged drought events were recorded in 2015-2018 and in 2024, when the duration of rainless periods reached 2-3 months [18, 19].

Conclusions

The study conducted using hydrometeorological station data operating within the territory of the Republic of Azerbaijan yielded the following results.

1. In the territory of Azerbaijan, during the period 1991-2025, compared to the climatological norm (1961-1990), the mean annual air temperature increased by 1.1°C. For the period 2007-2025, the increase was 1.3°C, while in 2025 alone it reached 1.8°C. In addition, mean annual precipitation decreased by 37 mm relative to the long-term norm, indicating that climate change has intensified over time.

2. In areas above 1000 m elevation within the country, the increase in temperature is more pronounced compared to other altitude intervals. For precipitation, both increases and decreases relative to the climatological norm are observed across all elevation bands; however, a consistent decrease is recorded exclusively in the 200–500 m elevation interval.

3. Under the influence of regional climate change, the mean annual river discharge volumes have decreased by 20-40%. Changes in the annual flow regimes of rivers have been observed, accompanied by increased variability, a reduction in flood discharge volumes, and a decline in peak flows. While winter low-flow conditions have increased, both the magnitude and duration of spring high-flow (flood) periods have decreased.

4. The analyses show that during the period 2020-2025 in the territory of Azerbaijan, 551 flood events and 431 hail events were recorded. The most severe drought occurred in 2024, while the strongest snow avalanche was recorded on December 16, 2000. Such events confirm the spatial and temporal intensification and expansion of the hazardous impacts of climate change.

5. Under the influence of climate change, the decline in the level of the Caspian Sea continues toward a critical threshold. Compared to its recent maximum level in 1995 (−26.04 m), the current level in 2025 (−29.05 m) has decreased by up to 3 meters. The reduction in the Caspian Sea level is explained by the impact of climate change on the decreasing water levels in inland water basins.

Under the influence of regional climate change, river flow regime alterations are occurring, characterized by a decrease in flood and high-flow (spring runoff) discharges and their peak values, along with an increase in winter low-flow conditions. Currently, there is a 4 km³ deficit in national water resources; however, the National Water Strategy projects that this deficit will increase to 8 km³ by 2040.

Under the influence of climate change, the emergence of spatiotemporal shifts in the recurrence of hazardous hydrometeorological events makes it necessary to periodically update adaptation and mitigation measures in settlement areas. In addition, the development of model-based forecasting and early warning systems across all regions will help reduce the expected safety risks. It is recommended that the results of this study be taken into account in the planning of all settlement, industrial, and tourism sectors. Future research should focus on the long-term frecasting of hazardous hydrometeorological events and the development of improved adaptation programs.

Конфлікт інтересів: автор повідомляє про відсутність конфлікту інтересів

Декларація про використання генеративного штучного інтелекту: автор підтверджує, що під час підготовки рукопису не використовувалися інструменти штучного інтелекту.

Conflict of Interest: The author declares no conflict of interest.

Declaration of use of generative artificial intelligence: The author confirm that no AI tools were used during the preparation of the manuscript.

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Вплив регіональної зміни клімату на небезпечні гідрометеорологічні явища в Азербайджані

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АНОТАЦІЯ

Спостережувані на даний момент зміни клімату на Землі мають свій вплив на всі регіони. Сучасне потепління більш помітно проявляється в середніх широтах. З часом зміни в просторово-часовій повторюваності небезпечних гідрометеорологічних подій вимагають постійного моніторингу поточного стану гідрометеорологічних елементів. Стаття присвячена впливу глобальної зміни клімату на регіональну зміну клімату в Азербайджані та небезпечним гідрометеорологічним подіям, які вона породжує, з особливим акцентом на річкових водних ресурсах. Коротко проаналізовано глобальну зміну клімату на Землі, а її регіональний вплив на територію Азербайджану досліджено на основі порівняльного аналізу нещодавніх та довгострокових історичних даних спостережень. У дослідженні річні показники кліматичних елементів були отримані за допомогою математичних та статистичних методів. Для моніторингу нещодавніх змін було проведено порівняльний аналіз між стандартними кліматичними значеннями (1961–1990) та відповідними показниками за коротші періоди часу. У дослідженні використано дані спостережень, зібрані з 61 діючої метеорологічної та 84 гідрологічних станцій Національної гідрометеорологічної служби, що працюють на території Азербайджанської Республіки. Набір даних охоплює період 1961–2025 років і включає вимірювання різних гідрометеорологічних елементів. Аналіз показує, що відносно багаторічної кліматичної норми (1961–1990 роки) середньорічне підвищення температури в країні становило 1,1°C за період 1991–2025 років, тоді як за 2007–2025 роки воно досягло 1,3°C. Однак лише у 2025 році це підвищення склало 1,8°C. За зазначені періоди спостерігається постійне зниження як річної кількості опадів, так і річкового стоку. Відбуваються значні зміни в режимах річкового стоку, включаючи зменшення обсягів стоку під час весняно-осінніх повеней та висоководних періодів, а також збільшення під час низьководних зимових періодів. Динаміка небезпечних гідрометеорологічних процесів, що спричиняють стихійні лиха в країні, посилюється у зв'язку з регіональною зміною клімату. Водночас наголошується, що отримані емпіричні результати повинні бути використані науковою спільнотою та враховані в різних прикладних та планових проєктах.

ІНФОРМАЦІЯ ПРО СТАТТЮ :

Рукопис надійшов
29 березня 2026

Отримано після рецензування
8 травня 2026

Затверджено до друку
25 травня 2026

Опубліковано онлайн
30 травня 2026

Ключові слова:

зміна клімату, температура повітря, атмосферні опади, річковий стік, водні ресурси, град, снігові лавини, екстремальні гідрометеорологічні параметри, повені, Азербайджан.

https://doi.org/10.26565/2410-7360-2026-64-18

УДК 504.3+528.8

Геопросторовий аналіз щільності шкідливих викидів в атмосферне повітря стаціонарними джерелами у Рівненському районі Рівненської області

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АНОТАЦІЯ

Атмосфера відіграє визначальну роль у функціонуванні біогеохімічних циклів. Вона бере участь у таких природних процесах, як дихання, фотосинтез, кругообіг води, теплообмін, а також виконує захисну функцію, оберігаючи земну поверхню від надлишкового сонячного випромінювання. Усе це свідчить про її важливе значення у підтриманні життя, кліматичного балансу та екологічної стабільності. Проте активна господарська діяльність людини може істотно погіршити якість повітряного середовища. У результаті техногенного впливу в атмосферу потрапляють численні шкідливі домішки, які негативно позначаються не лише на здоров'ї людей, а й на урожайності сільськогосподарських культур, стані ґрунтового покриву, водних екосистем та ін. У дослідженні проведено відбір та узагальнення статистичних даних стосовно викидів забруднювальних речовин і парникових газів в атмосферне повітря стаціонарними джерелами на території громад Рівненського району Рівненської області. Виконано обчислення щільності викидів з урахуванням площ територіальних громад, що дозволяє оцінити інтенсивність забруднення. Для здійснення обробки, візуалізації та аналізу інформації використано спеціальне програмне забезпечення ArcMap. Представлено авторські тематичні карти, на яких відображено розподіл щільності викидів забруднювальних речовин і парникових газів як загалом, так і за окремим групами (метали та їх сполуки, речовини у вигляді суспендованих твердих частинок, сполуки азоту, діоксид та інші сполуки сірки, оксид вуглецю, діоксид вуглецю, неметанові леткі органічні сполуки). Картографічне моделювання дозволило виявити потенційно проблемні території щодо несприятливої екологічної ситуації та встановити просторові закономірності їх розповсюдження. Отримані результати дослідження можуть бути практично застосовані органами місцевого самоврядування, екологічними службами, аналітичними структурами, окремими підприємствами та установами з метою ухвалення виважених управлінських рішень, розробки регіональної екологічної політики та впровадження заходів щодо зменшення техногенного тиску на навколишнє середовище в межах Рівненського району.

ІНФОРМАЦІЯ ПРО СТАТТЮ :

Рукопис надійшов
7 липня 2025

Отримано після рецензування
13 серпня 2025
Затверджено до друку

25 травня 2026

Опубліковано онлайн
30 травня 2026

Ключові слова:

атмосферне повітря, забруднювальні речовини, парникові гази, викиди, щільність забруднення, моніторинг, територіальні громади, геоінформаційні технології, тематичні карти.

Постановка проблеми

Атмосферне повітря є одним з найбільш важливих компонентів природного середовища і безпосередньо впливає на здоров'я людей, кліматичні процеси, стан екосистем. Уже впродовж тривалого часу простежується посилення техногенного впливу на атмосферу, зумовлене зростанням викидів шкідливих речовин від промислових підприємств, енергетичних об'єктів та інших стаціонарних джерел. Загроза від таких викидів обумовлена не лише їхнім хімічним складом, але й обсягами та тривалістю впливу на навколишнє середовище. У зв'язку з цим виникає потреба в систематичному моніторингу якості повітря та оперативному виявленні територій із підвищеним екологічним ризиком. До складу

Як цитувати : Остапчук Сергій, Остапчук Оксана, Лазарець Ольга (2026). Геопросторовий аналіз щільності шкідливих викидів в атмосферне повітря стаціонарними джерелами у Рівненському районі Рівненської області. *Вісник Харківського національного університету імені В.Н. Каразіна Серія «Геологія. Географія. Екологія»*, (64), 228–243. https://doi.org/10.26565/2410-7360-2026-64-18

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забруднювальних речовин, що потрапляють у повітря в результаті антропогенної діяльності, входить велика кількість хімічних елементів та їх сполук. Серед них особливо значущими є: метали та їх сполуки, суспендовані тверді частинки, сполуки азоту, діоксид та інші сполуки сірки, оксид та діоксид вуглецю, неметанові леткі органічні сполуки та ін.

Оцінка обсягів та просторового розміщення викидів дає змогу визначити рівень впливу техногенної діяльності на навколишнє середовище в межах окремих адміністративно-територіальних одиниць. Ефективним інструментом для візуалізації та аналізу такого роду відомостей можуть виступати геоінформаційні технології, які забезпечують інтеграцію просторових і статистичних даних, створення тематичних карт та здійснення інтерпретації відповідних показників. ГІС-технології уже традиційно активно застосовуються для моніторингу стану довкілля, дослідження рівня техногенного навантаження на територіях, розробки природоохоронних заходів та ін.

Аналіз останніх досліджень і публікацій

У сучасних умовах інтенсивного соціально-економічного розвитку як на глобальному рівні, так і в Україні, різноманітні питання, пов'язані із вивченням впливу техногенної діяльності на стан атмосферного повітря є непростим і комплексним завданням. Саме тому ця тема широко висвітлюється у науковій літературі, де розглядаються ті чи інші аспекти проблеми, аналізуються конкретні ситуації та застосовуються різні методики оцінювання.

У ході дослідження [1] проаналізовано динаміку викидів забруднювальних речовин в атмосферне повітря на території України за період з 2016 по 2020 роки. Встановлено, що загальний обсяг шкідливих викидів зменшився. Основну частку викидів утворюють стаціонарні джерела, тоді як пересувні джерела мають значно менший внесок. Незважаючи на загальну тенденцію до скорочення, високий рівень токсичного навантаження продовжує негативно впливати на густонаселені та промислово розвинені регіони. Аналіз структури викидів за видами економічної діяльності засвідчив, що найбільше забруднення атмосферного повітря спричиняють підприємства електроенергетики, видобувної та переробної промисловості.

Одним із ключових елементів системи моніторингу стану атмосферного повітря є вивчення процесу утворення шкідливих домішок та прогнозування рівнів забруднення з урахуванням типів макромасштабної циркуляції, характеристики приземного шару атмосфери та специфіки місцевих природно-географічних умов. Це має особливе значення для територій із високою концентрацією промислових об'єктів, які постійно спричиняють забруднення повітря. У статті [2] представлено результати аналізу основних умов, що впливають на якість повітря в різних районах Одеси.

Розглядається проблема забруднення атмосферного повітря в найбільш урбанізованих містах Волинської області – Луцьку, Ковелі, Нововолинську та Володимир-Волинському [3]. Проаналізовано фізико-географічні особливості розташування міст (рельєф місцевості, особливості атмосферної циркуляції тощо), демографічну ситуацію, щільність населення, а також наявність і характер промислового виробництва.

У публікації [4] висвітлено актуальні для органів місцевого самоврядування питання оцінки сучасного екологічного стану, виявлення екологічних проблем і формування перспектив сталого та безпечного розвитку Володимир-Волинської територіальної громади, що розташована у Волинській області. На основі аналізу природних ресурсів регіону, особливостей їхнього використання, рівня соціально-економічного розвитку, а також результатів реалізації місцевих екологічних програм, визначено перелік ключових екологічних викликів, що потребують першочергового вирішення.

Проаналізовано вплив об'єктів Лисичансько-Рубіжанського промислового вузла на екологічний стан окремих компонентів природного середовища, зокрема й атмосферного повітря [5].

Досліджено екологічні наслідки промислової діяльності на транскордонних територіях, зосереджуючи при цьому увагу на Чернігівській області [6]. Акцент зроблено на просторовому аналізі забруднення такими небезпечними речовинами, як важкі метали (ртуть, кадмій, свинець), нітрати, нафтопродукти та діоксид азоту. Ідентифіковано найбільш екологічно вразливі території та виявлено прямий взаємозв'язок між рівнем забруднення довкілля, ризиками для здоров'я населення та зниженням стійкості природних екосистем.

У роботі [7] описано створену автоматизовану систему для моніторингу забруднення повітря діоксидом азоту та оксидом вуглецю на території українських міст із використанням супутникових даних Sentinel-5P у режимі, наближеному до реального часу. Ця система забезпечує отримання детальної інформації про концентрацію NO_2 та CO в атмосфері над такими містами як Київ, Харків, Одеса та Кривий Ріг. При цьому вдалося визначити найбільш забруднені зони в межах кожного з цих міст.

При виконанні ландшафтно-екологічного планування території Харківської області створені картографічні моделі, що відображають стан

атмосферного повітря [8]. З'ясовано, що основну частку в забрудненні атмосфери складають діоксид сірки, діоксид азоту, оксид вуглецю та пил. За допомогою розроблених карт виявлено зони з найвищим рівнем забруднення, а також простежено динаміку змін викидів окремих речовин у часовому вимірі для всіх районів області.

Основною метою дослідження [9] є оцінка індексу якості повітря в Києві, ідентифікація основних джерел атмосферного забруднення та створення наочних екологічних карт. Для збору інформації використовувалися показники з 15 сенсорів міжнародної мережі AQI. У роботі представлено новий підхід до створення актуальних та візуально зрозумілих тематичних карт повітряного забруднення, які можуть бути використані екологічними службами та іншими зацікавленими сторонами.

У публікаціях висвітлено ключові фактори, які зумовлюють забруднення атмосферного повітря під впливом окремих стаціонарних джерел, як от під час буріння свердловин [10], діяльності свинокомплексів [11] та ін. Зазначено, що речовини, які викидаються в атмосферу, створюють потенційні загрози для довкілля та здоров'я людей.

Дослідження [12] спрямоване на підвищення ефективності управлінських рішень у сфері охорони навколишнього середовища шляхом застосування сучасних підходів до оцінки ризику для здоров'я населення, викликаного наявним рівнем забруднення атмосферного повітря. У статті запропоновано ієрархічну методику, яка дозволяє оцінювати небезпеку забруднення повітря на трьох рівнях – державному, регіональному та місцевому. Розроблена авторська методика враховує збереження поточних тенденцій антропогенного навантаження, а також імовірність виникнення надзвичайних ситуацій.

Пильну увагу даній тематиці приділяють і зарубіжні вчені. У їх працях досліджуються обсяги викидів в атмосферне повітря толуолу, етилбензолу та ксилолу з 26 нафтопереробних заводів у Нігерії [13], діоксиду сірки і діоксиду азоту прокатним виробництвом сталеливарного комплексу Сепід-Фараб Кавір в Ірані [14], твердих частинок, зокрема миш'яку, кадмію та хрому у високотемпературному міському середовищі Нанкіна у Китаї [15], виконується аналіз атмосферних викидів забруднювальних речовин та формуються висновки щодо рівня екологічної напруги в окремих населених пунктах у межах Кура-Араксинської рівнини Азербайджанської Республіки [16], у гірській долині Катманду у Непалі [17], розглядаються питання взаємозв'язку між викидами шкідливих речовин у повітря та рівнем захворюваності населення у промислово розвинутих містах Узбекистану – Навої та Зарафшан [18], густонаселених містах Пакистану [19], вплив забруднення повітря на серцево-судинні ризики мешканців Атланти, штат Джорджія, США [20] та ін.

Виділення невирішених раніше частин загальної проблеми. Наукові дослідження свідчать про те, що рівень забруднення атмосферного повітря змінюється з часом і характеризується значною просторовою нерівномірністю. Це зумовлює необхідність ретельного вивчення проблеми як у часовому, так і в територіальному аспектах. Важливо досліджувати зазначене питання й на рівні новоутворених адміністративних районів і територіальних громад України, оскільки у науковій літературі інформація про стан повітря в межах цих одиниць представлена вкрай обмежено.

Метою досліджень є картографічне відображення та аналіз щільності викидів забруднювальних речовин і парникових газів в атмосферне повітря стаціонарними джерелами у межах територіальних громад Рівненського району Рівненської області з подальшим визначенням зон із найбільш вираженою екологічною напругою.

Рівненський район для досліджень вибраний невипадково, адже серед чотирьох адміністративних районів області він вирізняється найвищими показниками: займає найбільшу площу (7216,6 км², що становить 36% території області), має найчисленніше населення (632,4 тис. осіб, або 55% жителів області), включає найбільшу кількість територіальних громад (26, що становить 40% від загальної кількості в області), а також характеризується значною концентрацією активних підприємств, що мають фіксоване місце розташування.

Серед таких стаціонарних джерел, які постійно або періодично забруднюють атмосферне повітря, варто виділити наступні:

- ПАТ «Рівнеазот» (с. Городок), належить до найбільших хімічних підприємств України, основна діяльність – виробництво мінеральних добрив. Забруднення: діоксид азоту, оксид вуглецю та ін.
- «Волинь-Цемент», філія ПрАТ «Дікергофф цемент Україна» (м. Здолбунів), основна спеціалізація – виробництво цементу. Забруднення: пил, діоксид сірки, діоксид вуглецю, оксиди азоту та ін.
- ПрАТ «Вераллія Україна» (м. Костопіль), головний вид діяльності – виробництво склотари. Забруднення: оксиди азоту, оксид вуглецю, пил.
- ПрАТ «Костопільський завод скловиробів» (м. Костопіль), скляне виробництво. Забруднення: пил, оксиди азоту, оксид вуглецю та інші речовини.
- ПрАТ «Консюмерс-Скло Зоря» (с. Зоря), скляне виробництво. Забруднення: пил, оксиди азоту, оксид вуглецю та інші речовини.

• ТзОВ «Свиспан Лімітед» (м. Костопіль), спеціалізується на виробництві деревостружкових плит. Забруднення: пил, формальдегід та інші органічні сполуки.

• ТзОВ «ОДЕК Україна» (с. Оржів), спеціалізується на виготовленні високоякісної фанери. Забруднення: оксид вуглецю, діоксид азоту, діоксид сірки та ін.

• ТзОВ «Кроноспан Рівне» (с. Городок), деревообробне підприємство, має більше 90 джерел викидів різних забруднювальних речовин.

• ТзОВ «Ізотерм-С» (м. Рівне), виробник будівельної продукції. Забруднення: пил, діоксид вуглецю, оксид азоту, оксид сірки.

Матеріал і методи досліджень

Для виконання досліджень використано офіційні відомості за 2024 рік, надані Головним управлінням статистики у Рівненській області [21]. Первинний масив даних подано у вигляді електронної таблиці (файл Microsoft Excel), у якій в розрізі територіальних громад вказано: загальні обсяги викидів (тонн за рік) та їх розподіл за видами забруднювальних речовин і парникових газів.

У рамках подальшого дослідження виконано попереднє структурування та уніфікацію даних, зокрема здійснено відбір інформації лише стосовно громад Рівненського району, розраховано щільність викидів як відношення обсягу викидів до площі громади (кг/км^2), перевірено відповідність назв територіальних громад для коректного з'єднання з просторовим шаром у ГІС.

Оброблені таким чином табличні дані завантажено до програмного середовища ArcMap (частина пакета ArcGIS), де їх приєднано до векторного шару адміністративного поділу Рівненського району. Для цього застосовано інструмент Join, який дозволив зіставити назви громад у статистичній таблиці з відповідними записами в атрибутивній таблиці просторового шару. Створення бази даних та заповнення таблиці атрибутів з відомостями щодо шкідливих викидів здійснено за стандартною процедурою.

З метою подальшої побудови тематичних карт було вибрано систему координат Pulkovo 1942 GK Zone 5, яка базується на рівнокутній поперечно-циліндричній проекції Гаусса-Крюгера. Такий підхід дозволяє мінімізувати картографічні спотворення та зберегти правильну і візуально звичну конфігурацію територій.

Виклад основного матеріалу. Створення тематичних карт є невід'ємною складовою геоінформаційного аналізу, оскільки дозволяє наочно відображати просторові особливості поширення викидів забруднювальних речовин в межах окремих територіальних громад. У рамках даного дослідження картографування здійснювалося на основі попередньо обчисленої щільності викидів. Застосування цього показника забезпечує можливість коректного порівняння між громадами з урахуванням їх територіальної площі, що підвищує об'єктивність оцінки та її придатність до просторової інтерпретації.

Основним способом відображення інформації на картах було обрано картограми. Для кожної карти використовувалася кольорова шкала з відповідними градаціями, що дозволяє легко ідентифікувати території з найвищими або найнижчими значеннями щільності викидів. У тих випадках, коли дані були відсутні, відповідні території позначалися білим кольором. Для кращої інформативності на картах зазначено середні значення щільності викидів як по окремих громадах, так і в цілому по району. Карти побудовано в лінійному масштабі, що сприяє зручності їх сприйняття та використання.

Всі картографічні матеріали створено за єдиною методикою. Це забезпечує їхню узгодженість і дає змогу проводити коректне порівняння відповідної інформації між різними територіальними громадами.

Поняття загальних викидів забруднювальних речовин охоплює повний обсяг усіх забруднювачів, що потрапляють в атмосферу з різних джерел на визначеній території протягом певного періоду. Цей індикатор дає змогу оцінити рівень забруднення повітряного середовища та простежити його зміни у динаміці.

Загальні викиди слугують важливим критерієм екологічного навантаження, оскільки включають як малонебезпечні сполуки, так і більш шкідливі речовини. Високі обсяги таких викидів, як правило, свідчать про значну інтенсивність антропогенної діяльності в регіоні, зокрема в галузях промисловості чи енергетики. Такі умови потребують підвищеної уваги з боку контролюючих органів. Регулярне перевищення середніх значень цього показника може спричинити низку негативних наслідків: порушення екологічної стабільності, погіршення здоров'я населення, особливо з боку органів дихання, зниження якості життя та деградацію природних екосистем.

На тематичній карті (рис. 1) відображено просторовий розподіл щільності загальних викидів забруднювальних речовин у межах територіальних громад Рівненського району.

Найвищі показники щільності зафіксовано в Городоцькій (17116,59 кг/км^2), Здолбунівській (12265,59 кг/км^2) та Рівненській (6862,12 кг/км^2) громадах. Така концентрація забруднень пов'язана з розміщенням на цих територіях значних джерел викидів, серед яких – велике хімічне виробництво, цементні заводи, котельні та об'єкти зі зберігання сировини.

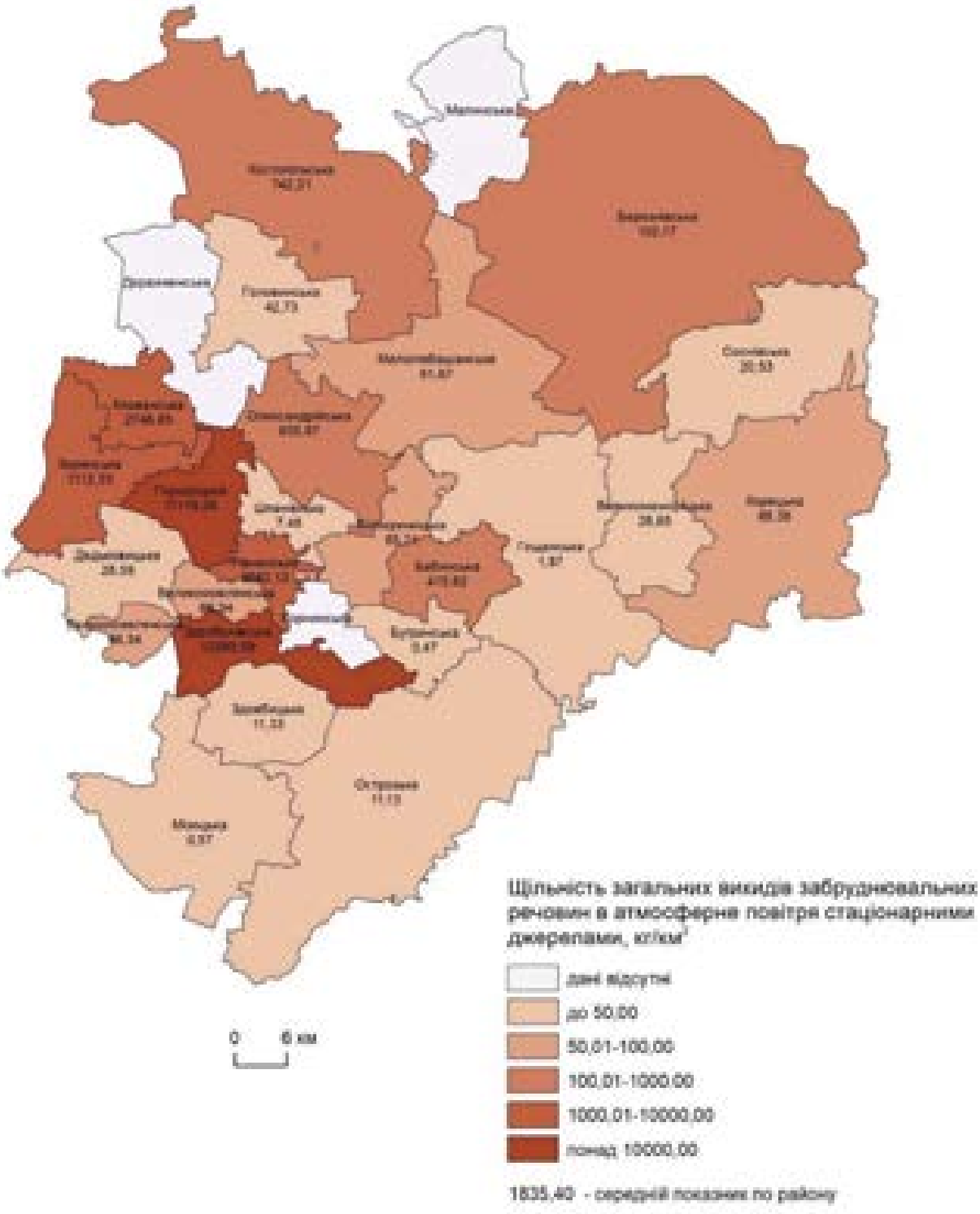


Рис. 1. Загальні викиди забруднювальних речовин /
Fig. 1. Total emissions of pollutants

Метали та їх сполуки – це хімічні речовини, серед яких свинець, кадмій, ртуть, миш'як та їхні органічні й неорганічні форми, що можуть потрапляти в повітря у вигляді пилу, парів або аерозолів, здебільшого як результат промислової діяльності.

Такі викиди становлять підвищену небезпеку через високу токсичність, здатність накопичуватися в живих організмах та тривалий період збереження в навколишньому середовищі. Важкі метали можуть спричиняти серйозні порушення в роботі життєво важливих органів: наприклад, свинець шкодить кровотворній системі, кадмій – уражує дихальні шляхи та опорно-руховий апарат.

Представлена карта (рис. 2) відображає розподіл щільності викидів металів та їх сполук. Найбільша щільність викидів зафіксована в Рівнен-

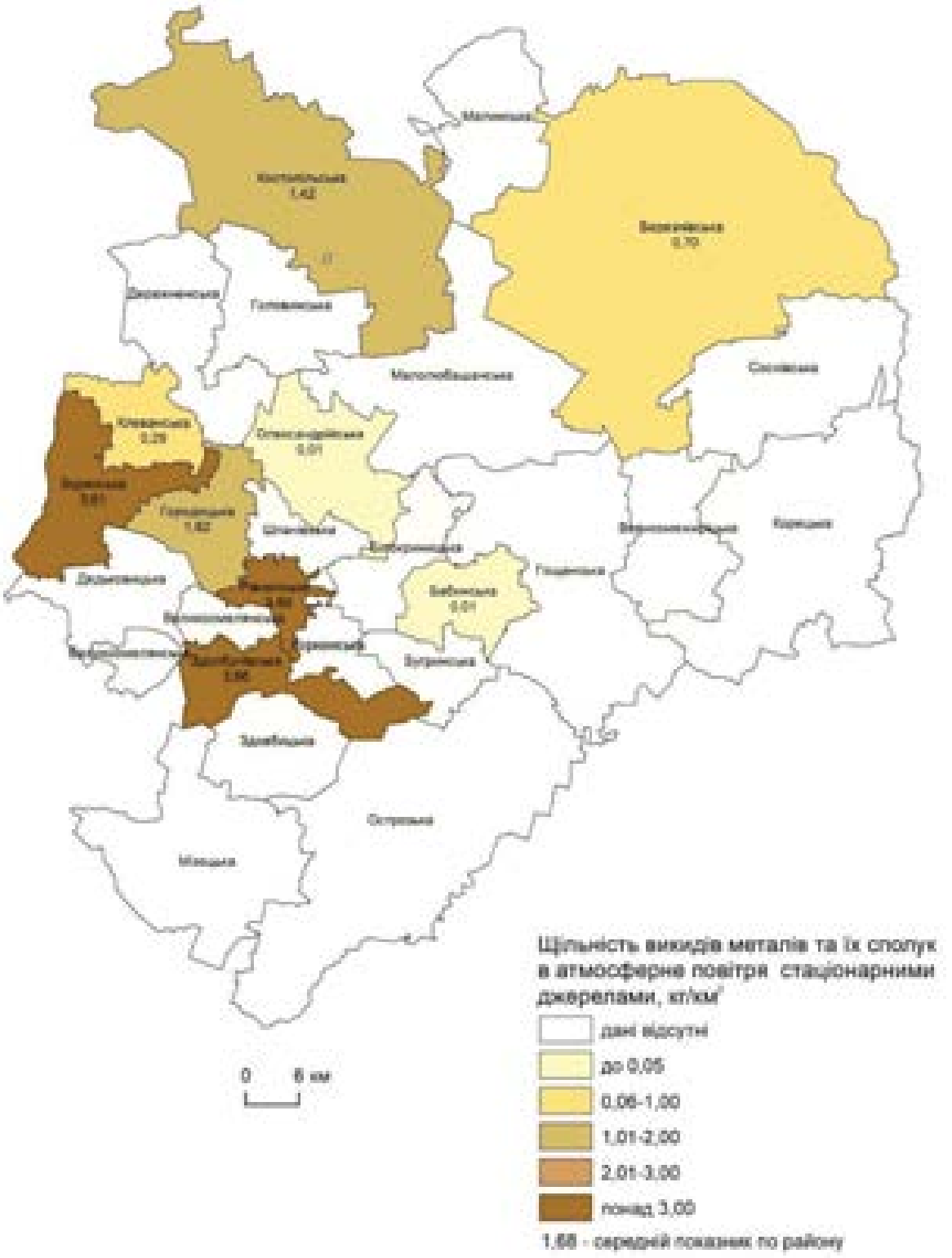


Рис. 2. Викиди металів та їх сполук
Fig. 2. Emissions of metals and their compounds

ській (3,80 кг/км²), Здолбунівській (3,66 кг/км²) та Зорянській (3,61 кг/км²) громадах.

Ці показники пов'язані з високим рівнем промислової активності на відповідних територіях (обробна, цементна), наявністю котельнь, полігонів твердих відходів. Картографічні дані чітко позначають зони локалізованого інтенсивного забруднення, що вказує на необхідність організації системи локального екологічного моніторингу, посилення природоохоронних заходів та впровадження контролю за викидами з боку відповідних об'єктів.

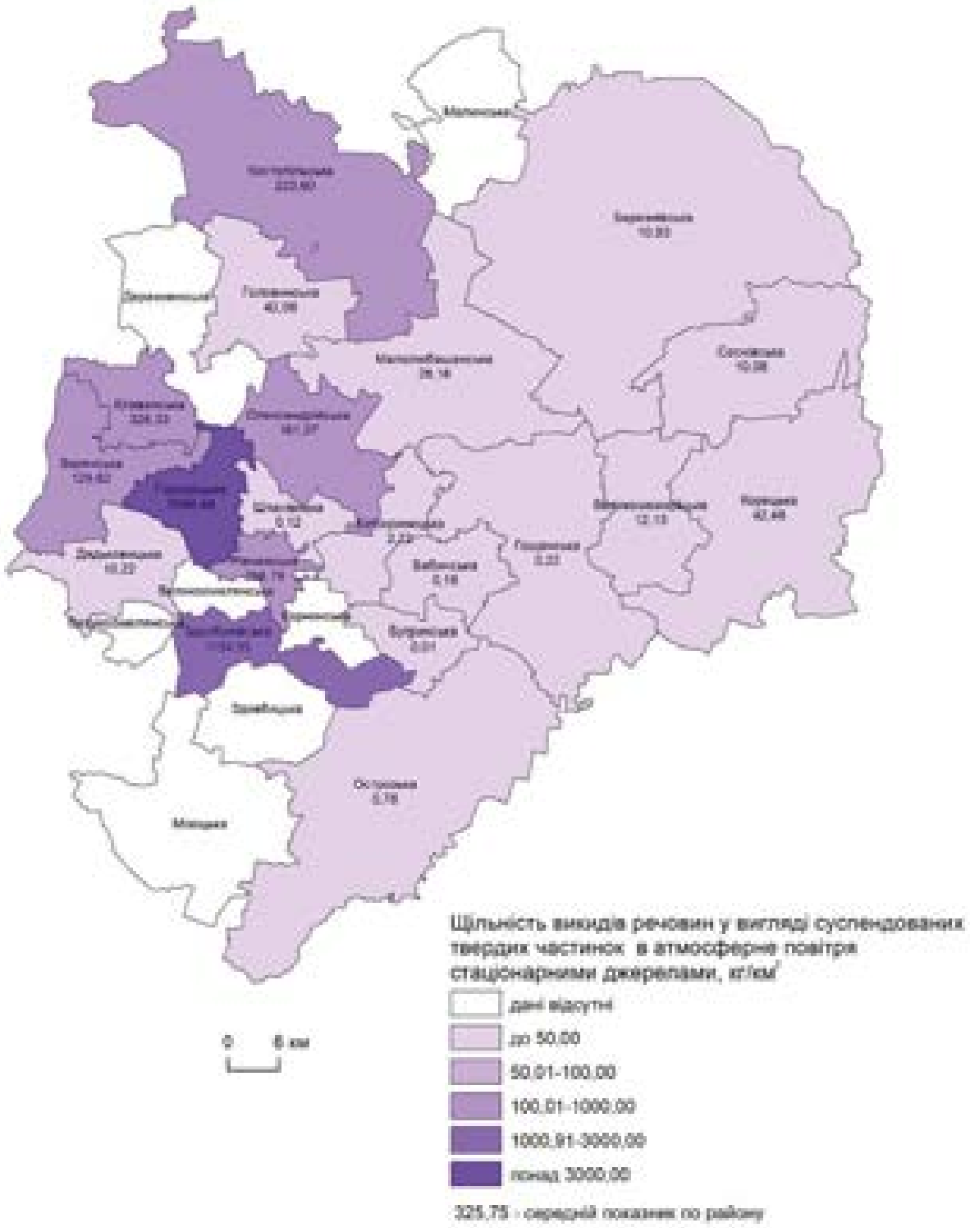


Рис. 3. Викиди речовин у вигляді суспендованих твердих частинок /
Fig. 3. Emissions of substances in the form of suspended solids

Суспендовані тверді частинки – це дрібні тверді частинки або краплі рідин, що знаходяться у завислому стані в атмосферному повітрі. Їх склад може бути різноманітним і включати нітрати, сульфати, органічні речовини, важкі метали, частинки ґрунту чи пилу, а також біологічні алергени, наприклад, спори грибів або фрагменти пилку.

На карті (рис. 3) відображено просторовий розподіл щільності викидів суспендованих твердих частинок в атмосферу.

Найбільше навантаження зафіксовано у Городоцькій громаді (3594,44 кг/км^2), а також у Здолбунівській (1154,55 кг/км^2), Рівненській (748,79 кг/км^2). Ці громади характеризуються наявністю активних промислових підприємств,

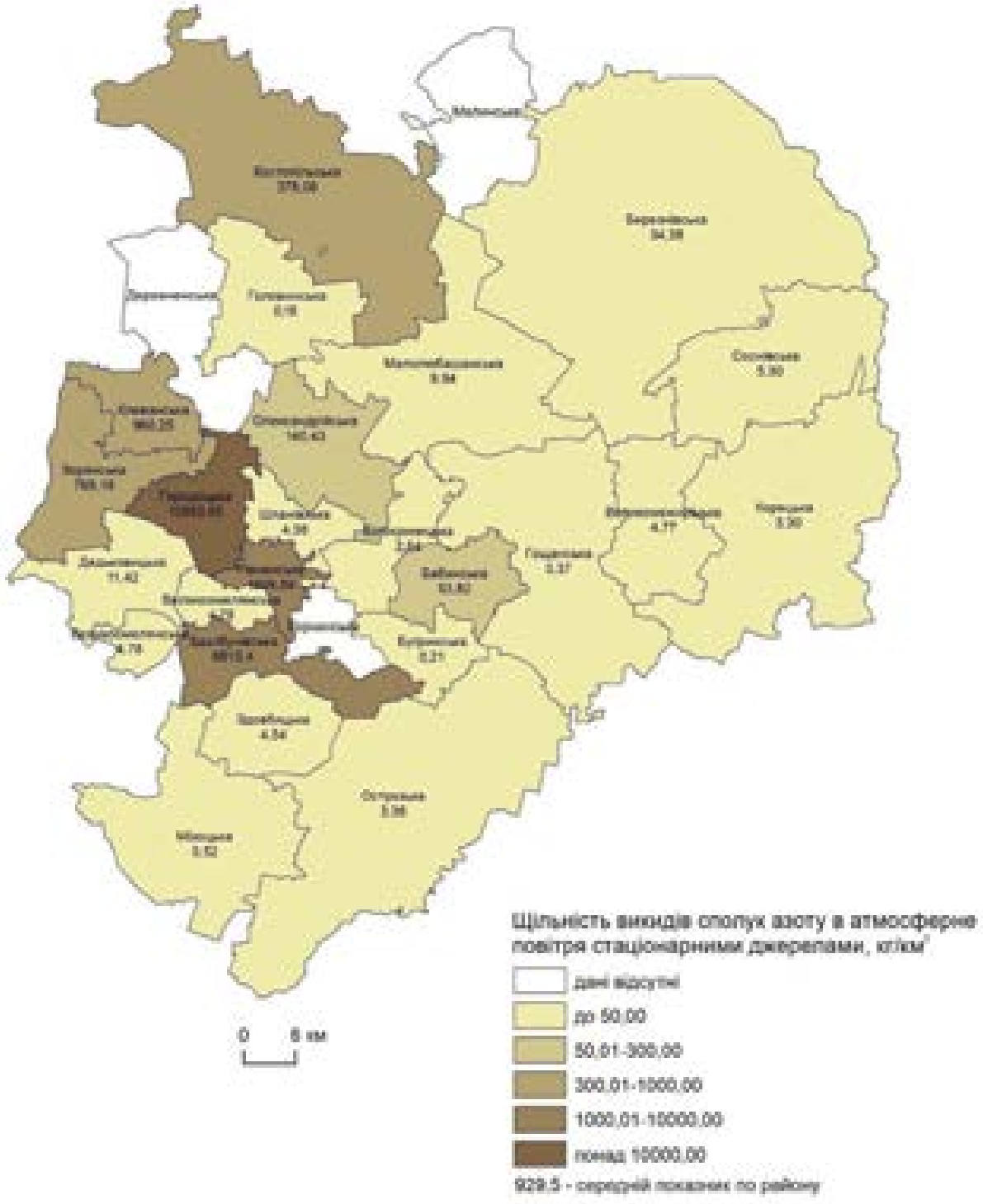


Рис. 4. Викиди сполук азоту
Fig. 4. Emissions of nitrogen compounds

котельнь, будівельних об'єктів, які є основними джерелами викидів твердих частинок в атмосферу. Натомість у громадах, де щільність викидів не перевищує 50 кг/км², переважають аграрні або лісові ландшафти з обмеженим техногенним впливом. Високий рівень концентрації твердих частинок в атмосферному повітрі вказує на потребу в удосконаленні систем очищення викидів та посиленні контролю за джерелами пилу. Це має особливе значення для щільно заселених промислових зон, де забруднення становить підвищену загрозу для здоров'я населення.

Азотисті сполуки в атмосфері представлені переважно оксидами азоту (NO_x), що утворюються як унаслідок природних процесів, наприклад, під час грозових розрядів або лісових пожеж, так і в результаті людської діяльності. У нижніх

шарах атмосфери ці речовини є нестабільними, оскільки швидко розпадаються під дією ультрафіолетового випромінювання та вологи.

Карта (рис. 4) ілюструє просторовий розподіл щільності викидів азотистих сполук.

Найвищі значення цього показника спостерігаються у Городоцькій (10563,65 кг/км^2), Здолбунівській (6813,4 кг/км^2) та Рівненській (1609,89 кг/км^2) громадах. Такий рівень забруднення пояснюється значною концентрацією промислових об'єктів, наявністю теплогенеруючих установок. Азотисті сполуки відіграють ключову роль у формуванні кислотних дощів та фотохімічного смогу, а також сприяють утворенню тропосферного озону. Їх підвищені концентрації в атмосферному повітрі мають безпосередній негативний вплив на здоров'я населення та стабільність природних екосистем.

Діоксид сірки (SO_2) – безбарвний газ із характерним різким запахом, що утворюється під час згоряння сірки або сірковмісних речовин. Цей газ є сильнокислою сполукою, яка у водному середовищі перетворюється на сірчану кислоту. Він є однією з причин виникнення кислотних дощів.

Присутність діоксиду сірки у повітрі погіршує якість атмосфери, спричиняє підкислення ґрунтів та водойм, пошкоджує рослинність і знижує врожайність сільськогосподарських культур. Крім того, у верхніх шарах атмосфери він утворює аерозолі, які сприяють виникненню туманів і утворенню вторинних забруднювачів, зокрема сульфатних частинок.

За представленою картою (рис. 5) видно, що основна концентрація викидів діоксиду сірки спостерігається у Здолбунівській (2861,96 кг/км^2) і Рівненській (668,95 кг/км^2) громадах. Це істотно перевищує середнє значення по району (199,09 кг/км^2). Підвищені показники засвідчують, передусім, негативний вплив виробництв цементу та різноманітних будівельних конструкцій і матеріалів.

Оксид вуглецю (CO) – це безбарвний газ, який не має запаху і утворюється внаслідок неповного згоряння органічного палива, такого як вугілля, газ, бензин, нафта чи деревина. Основними джерелами його надходження в атмосферу у нашому випадку є теплоенергетичні об'єкти, промислові підприємства, а також системи побутового опалення, склади пального, автозаправні станції.

На карті (рис. 6) зображено просторовий розподіл щільності викидів оксиду вуглецю. До найбільш забруднених у цьому плані громад належать: Городоцька (2488,20 кг/км^2), Здолбунівська (1365,92 кг/км^2) та Клеванська (1072,98 кг/км^2). Такий характер розподілу свідчить про значне техногенне навантаження в цих громадах. Виявлені зони з підвищеною щільністю викидів потребують особливої уваги з боку екологічних служб та впровадження заходів щодо зменшення забруднення.

Діоксид вуглецю (CO_2) – безбарвний газ, що не має запаху і природним чином міститься в атмосфері. Його утворення відбувається під час дихальних процесів живих організмів, розкладу органічної речовини, а також унаслідок спалювання викопних видів палива.

Діоксид вуглецю належить до основних парникових газів, що переважно надходить в атмосферу внаслідок діяльності промислових підприємств, роботи енергетичного сектору та об'єктів транспортної інфраструктури. Зростання його концентрації спричиняє серйозні екологічні наслідки, зокрема глобальне потепління, кліматичні зміни та закислення океанів. Крім того, надмірна присутність цього газу у повітрі негативно впливає на стан здоров'я людини, провокуючи респіраторні та серцево-судинні захворювання, а також погіршення когнітивних здібностей.

На карті (рис. 7) відображено щільність викидів діоксиду вуглецю у межах територіальних громад. Найвищі показники зафіксовано у Здолбунівській (4 825 501,42 кг/км^2) та Городоцькій (4 255 406,88 кг/км^2) громадах. Високі значення також спостерігаються в Рівненській (1 500 718,05 кг/км^2) громаді. Такі показники свідчать про наявність потужних джерел викидів, зокрема промислових об'єктів, котельнь, а також підприємств, що використовують викопне паливо.

Неметанові леткі органічні сполуки (НМЛОС) становлять широку групу органічних речовин, що характеризуються високою леткістю, тобто здатністю переходити у газоподібний стан при нормальних температурних умовах. До цієї групи належать такі речовини, як бензол, етанол, формальдегід, циклогексан, ацетон та інші органічні сполуки.

На карті (рис. 8) наочно представлено просторову неоднорідність щільності викидів неметанових летких органічних сполук у межах територіальних громад. Найвищі значення зафіксовано у Рівненській громаді (564,85 кг/км^2), Клеванській (360,52 кг/км^2), Городоцькій (307,26 кг/км^2), Олександрійській (90,28 кг/км^2).

Високий рівень забруднення в цих громадах пов'язаний із наявністю промислових об'єктів, де застосовуються або генеруються леткі органічні речовини, зокрема в процесах фарбування, лакофарбового виробництва, поліграфії, обігу нафтопродуктів та хімічного виробництва.

Висновки

У дослідженні, з метою оцінки щільності викидів забруднювальних речовин і парникових газів

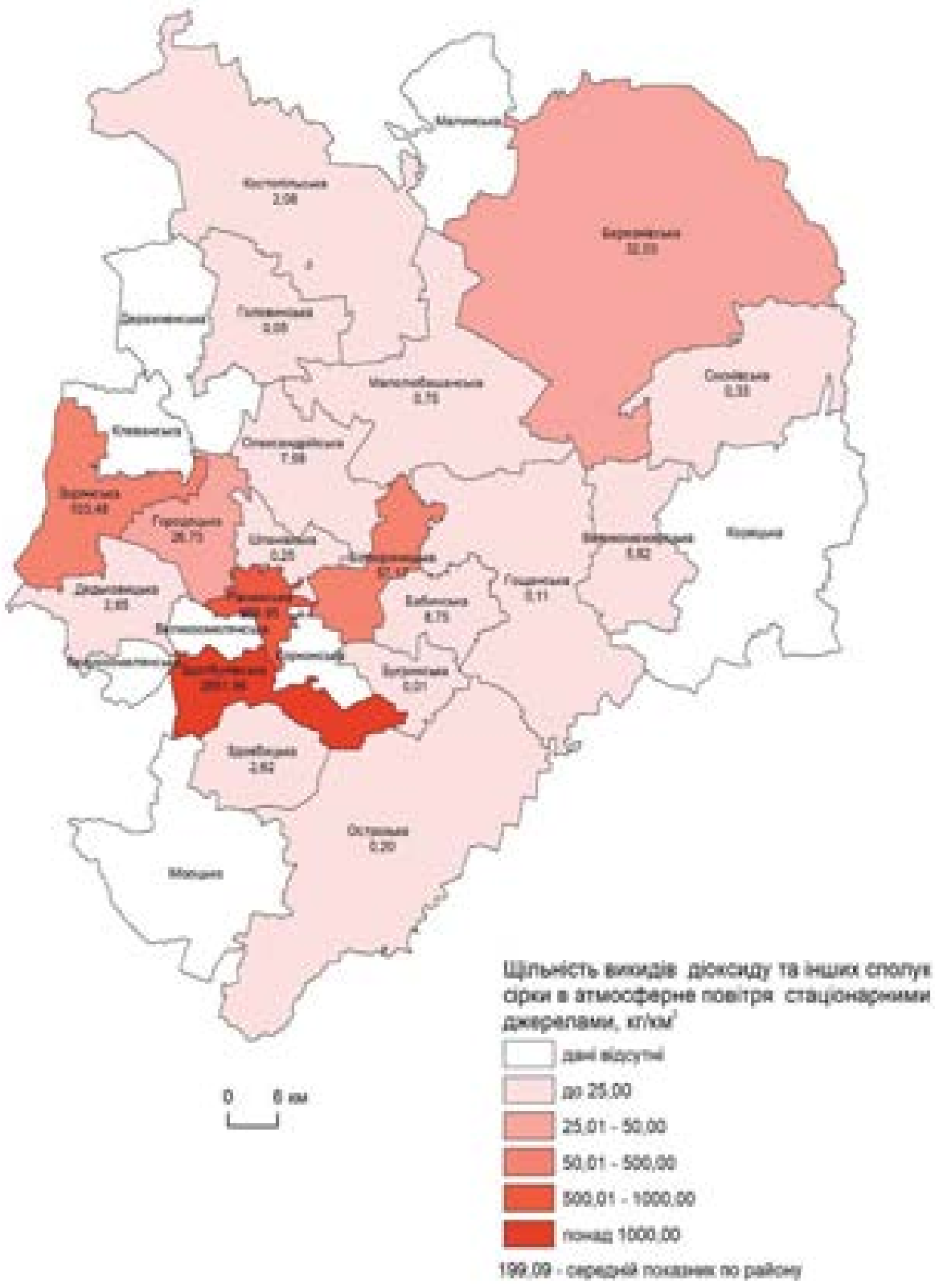


Рис. 5. Викиди діоксиду та інших сполук сірки
Fig. 5. Emissions of sulfur dioxide and other sulfur compounds

в атмосферне повітря у межах територіальних громад Рівненського району Рівненської області, поєднано методи статистичної обробки, геоінформаційного моделювання та просторового аналізу.

Створено тематичні карти стосовно щільності загального обсягу шкідливих викидів, так і кожного їх виду. У межах дослідження ідентифіковано територіальні громади з найвищими показниками щільності викидів та встановлено просторові закономірності їх розповсюдження. Найбільше занепокоєння, насамперед викликає стан повітря у Городоцькій і Здолбунівській

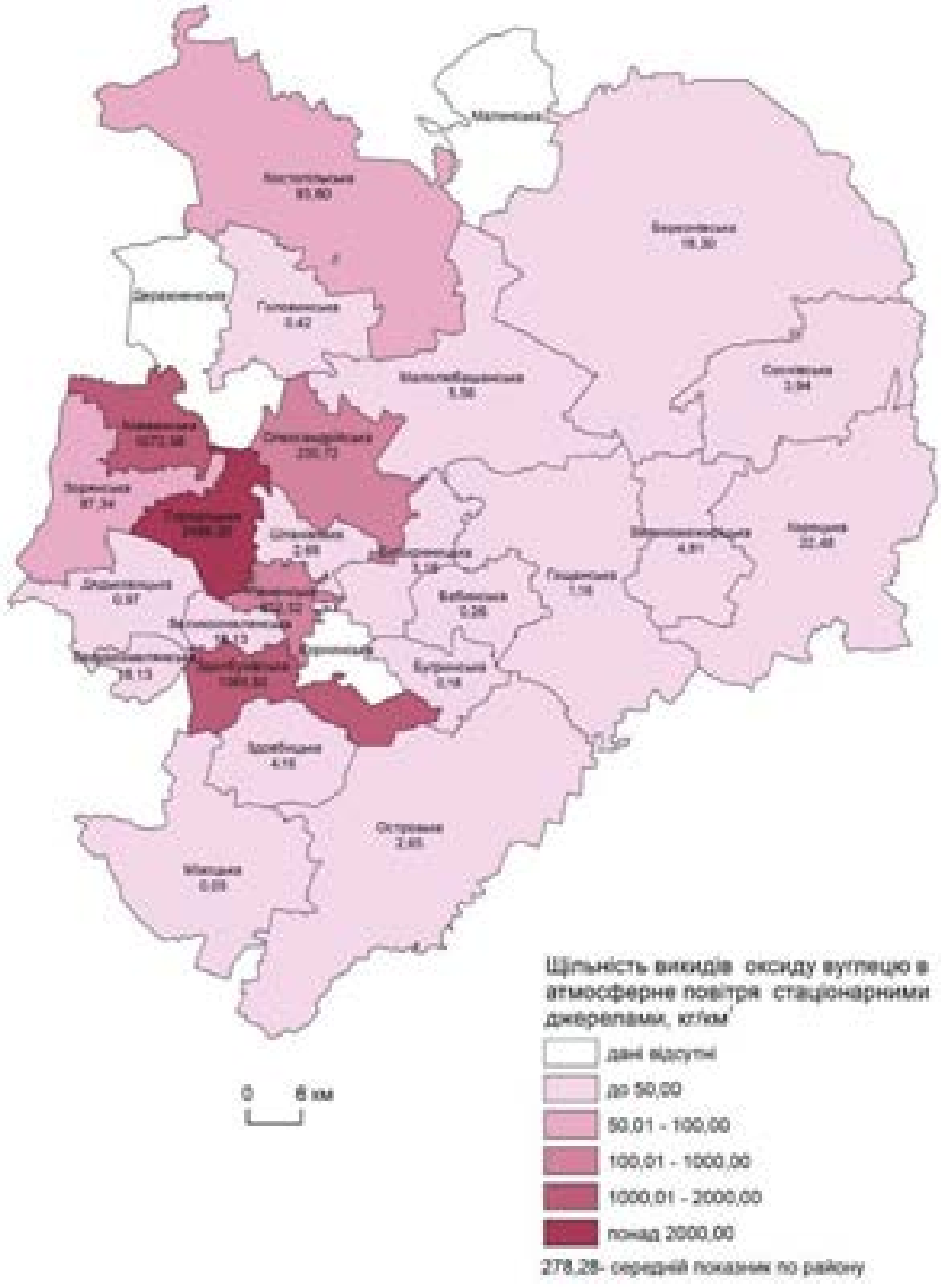


Рис. 6. Викиди оксиду вуглецю
Fig. 6. Carbon monoxide emissions

громадах, на території яких розміщено великі виробництва, відповідно, мінеральних добрив і цементу. Водночас, громади з найнижчими показниками викидів демонструють відносно благополучний стан атмосферного повітря, що свідчить про низький рівень антропогенного навантаження та сприятливі екологічні умови. Викладене вище підтверджує інформативність та точність застосованого геопросторового аналізу.

Отримані результати мають не лише ілюстративне значення, а й практичну цінність для органів місцевого самоврядування, екологічних служб та аналітичних центрів. Вони можуть

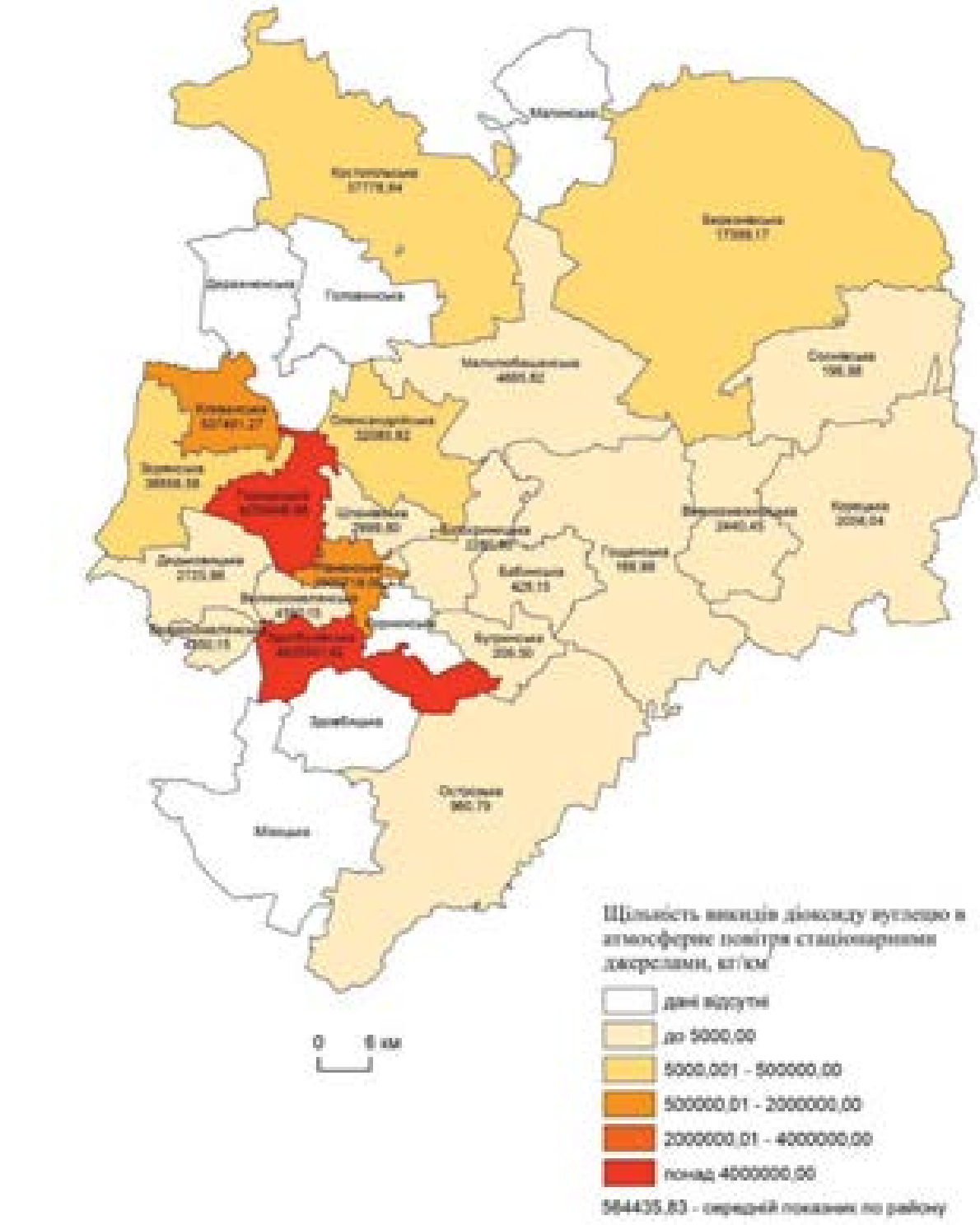


Рис. 7. Викиди діоксиду вуглецю
Fig. 7. Carbon dioxide emissions

слугувати основою для ухвалення обґрунтованих управлінських рішень, формування ефективної регіональної екологічної політики, а також планування цільових заходів, спрямованих на зменшення техногенного навантаження на довкілля в межах Рівненського району.

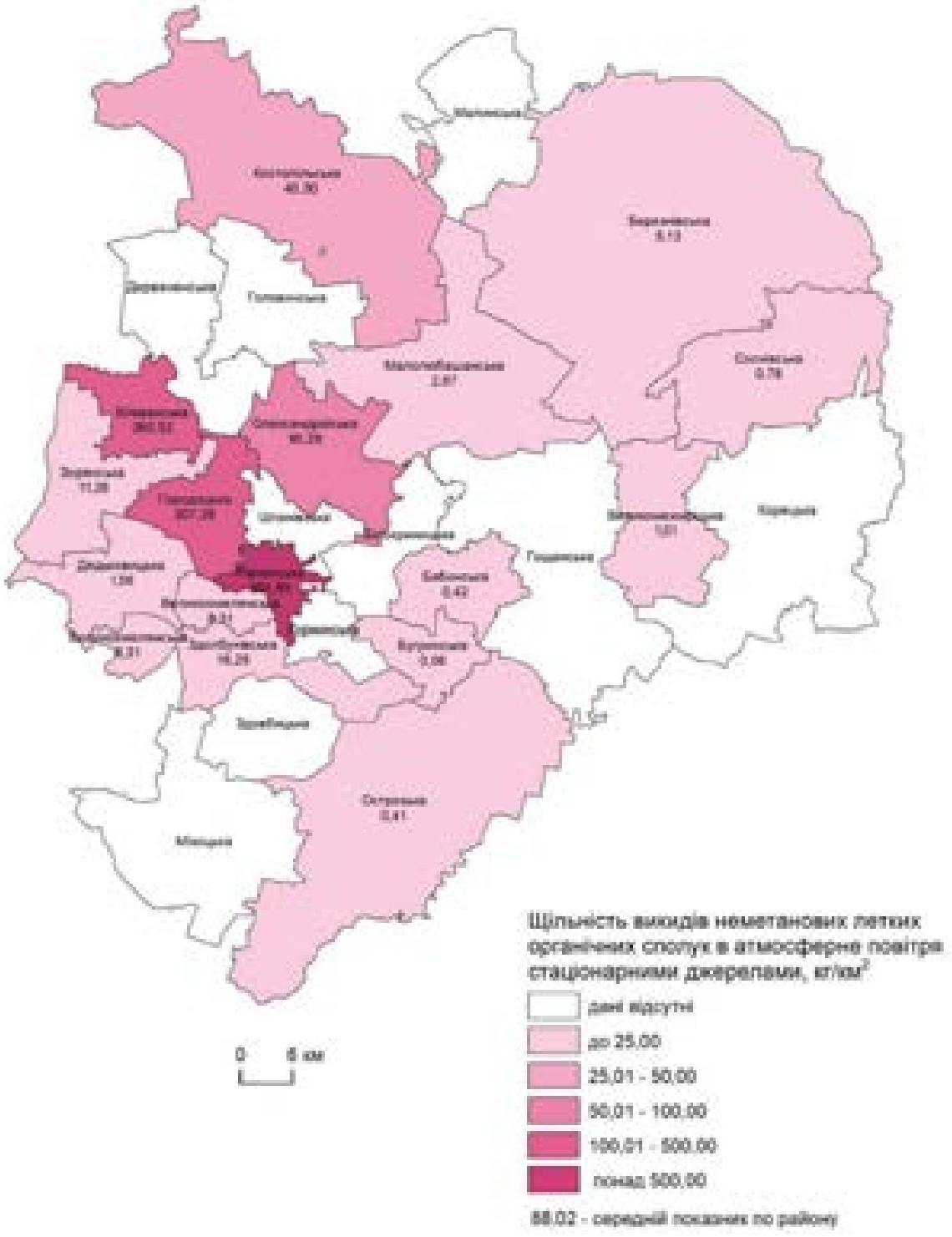


Рис. 8. Викиди неметанових летких органічних сполук
Fig. 8. Emissions of non-methane volatile organic compounds

Внесок авторів: всі автори зробили рівний внесок у цю роботу
Конфлікт інтересів: автори повідомляють про відсутність конфлікту інтересів.
Декларація про використання генеративного штучного інтелекту: автори підтверджують, що під час підготовки рукопису не використовувалися інструменти штучного інтелекту.

Authors Contribution: All authors contributed equally to this work
Conflict of Interest: The authors declare no conflict of interest

Declaration of use of generative artificial intelligence: The authors confirm that no AI tools were used during the preparation of the manuscript.

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Geospatial analysis of the density of harmful emissions into the atmosphere by stationary sources in Rivne district of Rivne region

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ABSTRACT

Problem statement. Active human economic activity can significantly degrade the quality of the air environment. As a result of anthropogenic impact, numerous harmful impurities are released into the atmosphere, which negatively affect not only human health but also crop yields, soil conditions, aquatic ecosystems, etc. Geoinformation technologies can be an effective tool for assessing the volume and spatial distribution of emissions, as they integrate spatial and statistical data, create thematic maps, and interpret relevant indicators.
Analysis of the latest research and publications. This topic is widely covered in the scientific literature by domestic and foreign scholars who consider certain aspects of the problem, analyze specific situations and apply various assessment methods.
The purpose of the research is to study, map, and analyze the density of pollutant and greenhouse gas emissions into the atmosphere by stationary sources within the territorial communities of Rivne district of Rivne region, with further identification of areas with the most pronounced environmental stress.
Material and methods of research. The research was based on official data for 2024 provided by the Main Department of Statistics in Rivne Oblast. The primary data set

ARTICLE INFO

Manuscript received
7 July 2025

Revised manuscript received
13 August 2025

Manuscript accepted
25 May 2026

Available online
30 May 2026

is presented in the form of a spreadsheet (Microsoft Excel file), which shows the total emissions (tons per year) and their distribution by type of pollutant and greenhouse gas by territorial community. The study combines methods of statistical processing, geographic information modeling, and spatial analysis.

Results. Using special ArcMap software, the authors developed thematic maps showing the distribution of pollutant and greenhouse gas emissions both in general and by individual groups (metals and their compounds, substances in the form of suspended solids, nitrogen compounds, sulfur dioxide and other sulfur compounds, carbon monoxide, carbon dioxide, non-methane volatile organic compounds). Cartograms were chosen as the main way to display information on maps. For each map, a color scale with appropriate gradations was used, which makes it easy to identify areas with the highest or lowest emission densities. All mapping materials were created using a single methodology. This ensures their consistency and allows for a correct comparison of relevant information between different territorial communities. The mapping modeling allowed us to identify potentially problematic areas with unfavorable environmental conditions and establish spatial patterns of their distribution. The air quality in the Horodok and Zdolbuniv communities, which are home to large-scale production of mineral fertilizers and cement, is of the greatest concern.

Scientific novelty and practical significance. Scientific novelty and practical significance. The geospatial analysis of pollutant and greenhouse gas emissions into the atmosphere by stationary sources within the territorial communities of Rivne district of Rivne region was performed on the basis of cartographic modeling. The results are of practical value for local governments, environmental services, and think tanks. They can serve as a basis for making informed management decisions, forming an effective regional environmental policy, and planning targeted measures aimed at reducing the technogenic load on the environment within the Rivne region.

Keywords:

atmospheric air, pollutants, greenhouse gases, emissions, pollution density, monitoring, territorial communities, geoinformation technologies, thematic maps

In cites: Ostapchuk Serhii, Ostapchuk Oksana, Lazarets Olga (2026). Geospatial analysis of the density of harmful emissions into the atmosphere by stationary sources in Rivne district of Rivne region. *Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology*, (64), 227–243. https://doi.org/10.26565/2410-7360-2026-64-18 [In Ukrainian]

https://doi.org/10.26565/2410-7360-2026-64-19

UDC: 551.583(575.6)

Observed changes in monthly maximum and minimum temperatures in the Nakhchivan Autonomic Republic (Azerbaijan) between 1961 and 2023

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ABSTRACT

Problem Statement. This study analyzes long-term spatiotemporal trends in monthly maximum and minimum air temperatures in the Nakhchivan Autonomous Republic for the period 1961–2023, using data from five meteorological stations to assess regional climate change.

Purpose. The study aims to develop and refine research methods for detecting climate-induced changes, with a particular focus on maximum and minimum air temperatures. Specifically, it seeks to establish robust statistical and spectral techniques that can identify temporal trends, diurnal variations, and extreme temperature events. By integrating observed temperature records with optimized analytical tools, the study intends to enhance the accuracy and reliability of regional climate assessments.

Methods. The study employed a combination of linear trend analysis, Pearson correlation, and anomaly-based methods to assess long-term variations in maximum and minimum air temperatures. Temperature anomalies were referenced to the 1961–1990 WMO climatological normal, and warming/cooling rates (°C/decade) quantified temporal trends. The use of non-parametric methods, moving time windows, and recurrence frequency analysis across temperature gradations enabled robust detection of long-term changes, recent shifts, and asymmetries in temperature distributions.

Results. For the period 1961–2023, a steady and widespread increase in maximum temperature has been established across all months and at all stations. The most intense warming is observed in winter, particularly in February (up to 1.180C/decade), in spring – March (up to 0.780C/decade), in summer – June to August (up to 1.50–2.090C/decade), and in autumn – September to October. The most statistically significant Tmax trends are characteristic of spring (up to 93% of cases) and summer (up to 87%), indicating the greatest stability of warming during the warm season. An analysis of different climatic periods reveals an intensification of warming rates in maximum temperature over time, especially after the 1980s and most prominently during 1991–2023. Minimum temperature demonstrates a more complex and heterogeneous behavior, including steady warming in winter, mixed trends in spring, localized cooling in summer (July), and pronounced spatial contrasts in autumn. Frequency analysis of temperatures indicates an expansion of the Tmax range from −90C to 420C, an increase in the recurrence of high temperatures (30–360C), and a rare but persistent occurrence of extremely high values (up to 420C). The comparison of Tmax and Tmin confirms that contemporary warming is asymmetric, with a dominant increase in daytime temperatures. Spatial differences are determined by topography. Overall, it has been established that the region's climate is characterized by increasing temperature extremity, a rising frequency of high-temperature classes, and enhanced interseasonal and inter-station contrasts.

Conclusions. Seasonal variations in temperature changes are particularly important in this region, where agriculture and the transportation sector hold substantial economic significance. Rapid increases in maximum temperatures during spring and summer could adversely affect various economic sectors in the coming decades. Such studies are essential for understanding climate change and play a crucial role in monitoring and analyzing climate trends to support policymakers in mitigation and adaptation strategies.

ARTICLE INFO

Manuscript received
9 February 2026

Revised manuscript received
29 April 2026

Manuscript accepted
25 May 2026

Available online
30 May 2026

Keywords:

Nakhchivan AR of Azerbaijan, climate change, maximum and minimum temperature anomalies, linear trend, temperature gradation, different climatic periods, frequency of high-temperature classes, asymmetric warming of maximum and minimum temperatures.

Introduction

In the context of ongoing global climate warming, changes in extreme air temperature indicators – particularly maximum and minimum values – are recognized as key signals of transformations within regional climate systems. Contemporary research indicates that not only

In cites: Safarov Surkhay (2026). Observed changes in monthly maximum and minimum temperatures in the Nakhchivan Autonomic Republic (Azerbaijan) between 1961 and 2023. *Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology*, (64), 244–264. https://doi.org/10.26565/2410-7360-2026-64-19

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shifts in mean temperature but also changes in the tails of the distribution (i.e., extremes) exert disproportionately strong impacts on natural and socio-economic systems.

Extreme temperature events – such as heatwaves, cold spells, and nocturnal frosts – have been shown to adversely affect agricultural productivity, income stability, and plant reproductive processes. At the same time, adaptive measures, including targeted irrigation, improved soil management, and regulation of diurnal temperature range (Tmax–Tmin), can partially mitigate these negative effects and enhance ecosystem resilience [24; 25; 34; 35].

Moreover, temperature extremes contribute to reductions in economic productivity and household welfare, while also posing significant risks to human health, including increased mortality, higher rates of hospital admissions, impaired child nutrition, and disruptions in biological processes [1; 4; 8; 33; 36]. Even relatively small increases (on the order of 1–2 °C) in maximum and minimum air temperatures may exceed species-specific tolerance thresholds, leading to substantial impacts on ecosystems, agriculture, and socio-economic systems, and thus playing a critical role in climate vulnerability assessments and the development of effective adaptation strategies [13; 18].

In this regard, the statistical analysis of long-term variability and trend components of monthly maximum and minimum temperature series is of fundamental importance for detecting regional climate change patterns. In the Nakhchivan Autonomous Republic (AR) of Azerbaijan, characterized by a continental and semi-arid climate, changes in the thermal regime directly affect water resource formation, agricultural productivity, energy demand, and ecosystem stability. Therefore, investigating the temporal behavior of temperature extremes in this region represents a scientifically and practically significant task.

Global studies show spatiotemporal variability of maximum and minimum temperatures, with 1951–1990 observations revealing asymmetric warming – minima rising ~0.84 °C, roughly three times maxima (~0.28 °C) across hemispheres – and 1946–2000 trends indicating widespread increases, particularly in winter and spring, with accelerated warming in the 1980s–1990s [15].

The regional results of maximum and minimum temperature changes and the results of other studies related to air temperature changes can be briefly summarized as follows.

Observed trends in North America, Europe, China, Russia, and Australia indicate increases in both maximum and minimum temperatures, with more pronounced warming in minimum temperatures, particularly during winter and spring. Daily analyses reveal hotter days and milder nights, reflecting significant nocturnal warming and intensified temperature extremes, which exhibit notable seasonal and regional variability [15; 19].

Between 1950 and 2018, Europe experienced widespread warming, with maximum temperatures showing smooth spatial patterns and notable increases in extreme heat events [2]. In northeastern Spain (1960–2006), minimum temperatures rose markedly in winter and spring, while maximum temperature changes were minor or spatially heterogeneous [7].

Long-term air temperature changes in central Ukraine using continuous meteorological records were analyzed in [11]. Winter and spring temperatures exhibit significant warming trends, with record-high annual averages in recent years (2020–2021). These results reflect a clear regional manifestation of climate warming, with implications for local climate variability, ecosystem responses, and adaptation in agriculture and water resource management.

The study of analyzing of spatiotemporal air temperature changes across Ukraine (1970–2014) using hydrometeorological data given in [16]. Significant warming trends were observed, with annual increases of 3.1–3.5 °C and pronounced summer variability. Regional differences show stronger warming in eastern than western Ukraine. The study demonstrates the value of hierarchical statistical methods for assessing seasonal and multi-decadal temperature dynamics and their ecological and socioeconomic impacts.

The study [22] examines heat wave characteristics and trends in selected Ukrainian cities under regional climate change. Using historical meteorological data and RCP scenarios (2.6, 4.5, 8.5) through 2050, results show that while annual heat wave frequency is lowest in southern Ukraine, duration and intensity vary regionally. Projections indicate an increase in heat wave days, especially during the cold season (October–April), highlighting temperature extremes' complex impacts on public health, agriculture, and infrastructure resilience.

Long-term temperature trends in Turkey indicate general increases in maximum temperatures (1929–1999), with exceptions in Central Anatolia, the Black Sea, and parts of Eastern Anatolia, and slight autumn declines [27]. Minimum temperatures rose significantly at many stations, especially in spring and summer, while winter and autumn trends were regionally mixed. From 1970–2014, both annual maximum and minimum temperatures increased notably in the Middle Fırat region [6], whereas in Mediterranean coastal zones (1970–2010), maxima rose significantly but minima showed a non-significant decline [12].

This study [23] integrates statistical, spatial, and thermodynamic analyses to examine temperature dynamics in the Lake Sevan basin. Long-term observations reveal a century-scale

warming trend with distinct warming periods, highlighting that a physical understanding of temperature enhances the interpretation of regional climate variability and supports broader climate change assessments.

A study conducted in Central Asia indicates that in recent decades, both maximum and minimum temperatures have exhibited increasing trends, contributing to a higher frequency of heatwaves [17].

In Lahore (Pakistan), minimum temperatures have steadily increased annually and seasonally, while maximum temperatures generally declined. Sub-period analysis (1988–2003 vs. 2004–2019) shows no significant changes in minima and rising maxima in the first period, whereas both minima and maxima increased in the second period [31].

As evidenced by the above analyses, the study of regional manifestations of climate change has become one of the key priorities of the international scientific agenda in recent years.

However, in the strategically important Nakhchivan AR of Azerbaijan, the long-term variability of temperature extremes has not yet been investigated in a sufficiently systematic and comprehensive manner.

The **main objective of this study** is to identify and evaluate long-term trends, variability, and statistical characteristics of monthly maximum and minimum air temperature series in the Nakhchivan AR over the period 1961–2023.

The **object** of the research is the observational series of monthly maximum and minimum air temperatures recorded at meteorological stations within the Nakhchivan AR.

The **subject** of the research is the temporal variability, trend structure, and statistical properties of monthly maximum and minimum temperature series, including their interpretation as indicators of regional climate change.

The Nakhchivan AR (5,363 km²) in southwestern Azerbaijan, spanning the Lesser Caucasus and Middle Aras Depression and bordering Armenia, Iran, and Turkey, is predominantly mountainous with Daralayaz and Zangazur ranges covering two-thirds of the territory and lowlands along the Aras River; elevations range from ~600 m to 3,906 m (mean ~1,400 m), with pronounced hypsometric and geomorphological heterogeneity influencing regional climate and local meteorological conditions [3]. Complex topography, continental climate, variable hydrology, vegetation, and anthropogenic influences have shaped three main soil types; climatic and edaphic constraints limit vegetation to xerophytic communities, while agricultural land use remains uneven due to rugged relief, climatic limits, and chronic irrigation constraints.

The Nakhchivan AR, Azerbaijan's most continental region (continentality index 60–80%), shaped by inland location, complex relief, and high solar radiation, exhibits active temperature sums of 2,000–4,500 °C and a frost-free period of ~210–230 days; seasonal evolution features subzero winter minima, rapid spring–midsummer warming, and autumnal declines in all temperature indicators with rising precipitation and humidity, while precipitation increases with elevation and is slightly higher in the east than the west [21].

The meteorological station network provides representative coverage of Nakhchivan AR's diverse physiography, with coordinates and elevations summarized in Table 1 and spatial distribution relative to major landscape units shown in Figure 1, enabling robust assessment of climate variability in relation to topography and landscape heterogeneity and ensuring reliable regional climatic analysis.

Data Sources. Daily maximum and minimum temperatures, reflecting daytime and nighttime thermal conditions, were averaged monthly from 1961–2023 observations obtained from the National Meteorological Data Bank of Azerbaijan [20] and used to characterize diurnal cycle periods and long-term climatic trends.

Air maximum and minimum temperatures for 1961–2023, along with several related indices, were calculated using a FORTRAN algorithm within the Norton Commander interface, with statistical analysis and graphical visualization performed in MS Excel to comprehensively assess temporal trends and spatial variations in temperature extremes across the study area.

Methods

Linear Tendency Estimation Method and Pearson correlation coefficient. A linear trend method was applied to assess long-term variations in maximum

Table 1

Main indicators of the Hydrometeorological stations

Stations	Altitude, m	Geographic latitude, north latitude	Geographic longitude, east longitude
Ordubad	861	38.9	46.0
Julfa	736	39.0	45.6
Nakhchivan	885	39.2	45.4
Shahbuz	1205	39.4	45.6
Sharur	812	39.6	45.0



Fig. 1. Location of the study area and spatial distribution of the meteorological stations

and minimum temperatures across Nakhchivan AR, with Pearson correlation [28] used to quantify the strength and direction of monthly temperature–time relationships, serving as the primary criterion for evaluating the significance and intensity of temporal trends across the study area.

Methodology to Analyse Anomalies, Trends and Gradations. Temperature anomalies for Tmax and Tmin (1961–2023) were calculated from monthly averages of daily values at all stations, referenced to the 1961–1990 WMO standard climatological normal to ensure consistency and comparability with previous studies [30].

To ensure a more comprehensive assessment of maximum and minimum temperature anomalies, their normal values for the period 1961–1990, calculated and evaluated by the author, are presented in Tables 2 and 3, respectively.

In December, depending on altitude and topography, the maximum air temperature varies within 5.0–7.2 °C, while the minimum ranges from −0.6 to 3.2 °C. In January, although maximum temperatures in the Nakhchivan AR remain above zero, minimum temperatures are negative throughout the entire region. In February, maximum temperatures are positive across the area, whereas minimum temperatures remain below zero.

From March to July, maximum air temperature increases from 10.4–14.1 °C to 31.8–34.7 °C, while minimum temperature rises from −0.2–2.5 °C to 18.4–23.5 °C. During the autumn months,

Table 2

Monthly and annual values of maximum air temperature norms in Nakhchivan AR, °C (for 1961-1990)

Station	The number of months												Year
	01	02	03	04	05	06	07	08	09	10	11	12	
Ordubad	3.4	6.3	13.3	20.0	25.2	29.5	31.8	31.4	28.3	21.5	14.1	7.1	19.3
Julfa	3.2	6.3	14.1	20.9	26.7	31.7	34.7	34.1	30.6	22.8	14.3	7.2	20.5
Nakhchıvan	1.5	4.4	12.7	19.6	25.1	30.5	34.5	34.0	29.7	21.8	13.7	6.0	19.4
Shahbuz	1.4	3.8	10.4	16.9	22.4	27.7	31.9	31.7	27.6	19.7	11.8	5.0	17.5
Sharur	1.0	3.9	12.4	19.1	24.4	29.6	33.9	33.3	29.0	20.0	12.7	5.6	18.8

Table 3

Monthly and annual values of minimum air temperature norms in Nakhchivan AR, °C (for 1961-1990)

Station	The number of months												Year
	01	02	03	04	05	06	07	08	09	10	11	12	
Ordubad	-4.5	-2.6	2.5	8.1	12.6	16.9	20.7	20.0	15.8	9.7	4.1	-0.6	8.5
Julfa	-5.4	-3.0	2.2	8.3	13.5	18.7	23.5	22.6	17.2	9.6	3.3	-1.3	9.1
Nakhchıvan	-7.0	-4.6	1.1	7.2	11.7	15.8	19.7	19.1	14.4	8.4	2.6	-2.2	7.2
Shahbuz	-7.2	-5.5	-0.2	5.8	10.1	14.4	19.1	18.5	13.5	7.2	1.9	-3.2	6.2
Sharur	-7.8	-5.6	0.3	6.5	10.7	14.6	18.4	17.6	12.8	6.5	1.5	-3.2	6.0

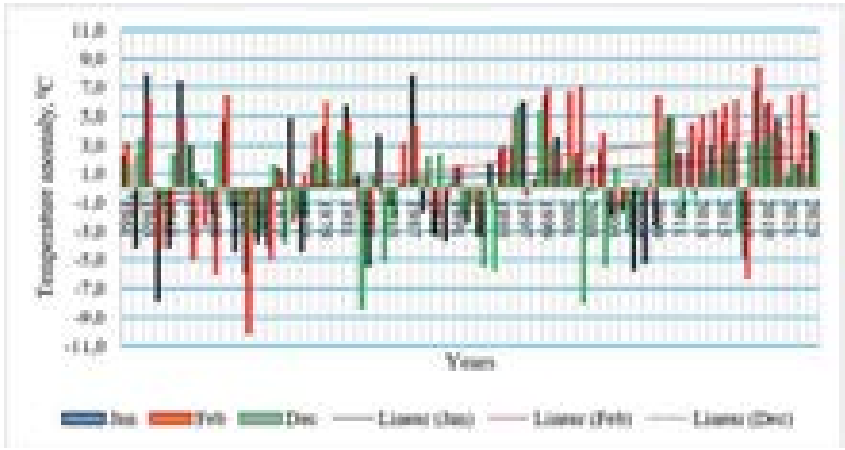


Fig. 2. Time variation trend in the mean monthly maximum temperature anomalies in winter season on the Nakhchivan AR

all temperature indicators show a decline. The long-term mean annual maximum temperature ranges from 17.5 to 20.5 °C, while the minimum temperature varies between −6.0 and 9.2 °C.

Temperature anomalies were calculated relative to the 1961–1990 baseline period:

$$T_{Ai}=T_i - T_{1961–1990}, \qquad (1)$$

where T_{Ai} – is the anomaly, T_i– is the observed temperature, and $T_{1961–1990}$ is the long-term mean for the corresponding month.

The rate of warming or cooling (°C/decade) was used to quantify long-term temperature changes, providing a standard WMO- and IPCC-endorsed metric that facilitates comparison across studies and spatial scales, reflects trend intensity, supports analysis of climate extremes and model projections, and enhances reliability by reducing interannual variability under non-stationary conditions [9; 10; 14; 30].

Combining non-parametric methods with decreasing and moving time series provides robust assessment of temperature trends across multiple temporal scales, with successively shorter periods (1961–2023 to 1991–2023) capturing long-term and recent changes, and 30-year moving windows, consistent with WMO standards, enabling comparable trend analysis and detection of temporal anomalies [5].

Analyzing recurrence frequencies of maximum and minimum temperatures across predefined gradations provides a robust assessment of extreme event intensity, persistence, and spatial characteristics, enabling evaluation of long-term warming or cooling, asymmetries toward higher values, and increases in heat extremes at annual and seasonal scales, while supporting statistical analyses using histograms, empirical distribution functions, percentile-based metrics, and extreme indices, and facilitating climate risk assessment, model validation, regional anomaly detection, and updating of climate norms [15; 26; 29; 32].

Results and Discussion

Long-term Dynamics of Monthly Mean Maximum and Minimum Temperature Anomalies (1961–2023). In this stady anomalies of maximum anda minimum temperatures are calculated in relation to the 1961–1990 reference period.

Long-term winter anomalies of monthly mean maximum and minimum temperatures in Nakhchivan AR (relative to 1961–1990) show a general warming trend from 1961 to 2023, with seasonal variation. Maximum temperature increases are strongest in February (0.92 °C/decade), weakest in December (0.21 °C/decade), and intermediate in January (0.46 °C/decade), with February trends statistically significant. Interannual variability and seasonal differences are summarized in Figure 2 and in Table 4.

Figure 2 shows that, overall, positive winter maximum temperature anomalies in Nakhchivan

Table 4

Some statistical characteristics of the long-term trends of area-averaged monthly maximum and minimum temperature anomalies across the Nakhchivan AR for the period 1961–2023

		Number of month											
		01	02	03	04	05	06	07	08	09	10	11	12
ΔTmax	^{0}C/decade	0.46	**0.92**	0.59	0.43	0.30	0.55	0.46	0.55	0.36	0.37	0.12	0.21
	r	0.21	**0.43**	**0.39**	**0.36**	**0.31**	**0.51**	**0.50**	**0.55**	**0.37**	**0.38**	0.10	0.12
ΔTmin	^{0}C/decade	0.17	0.49	0.34	0.06	-0.03	0.16	-0.05	0.17	0.27	0.15	-0.02	-0.02
	r	0.08	**0.28**	**0.30**	0.08	-0.02	0.23	-0.08	**0.29**	**0.44**	0.19	-0.02	-0.01

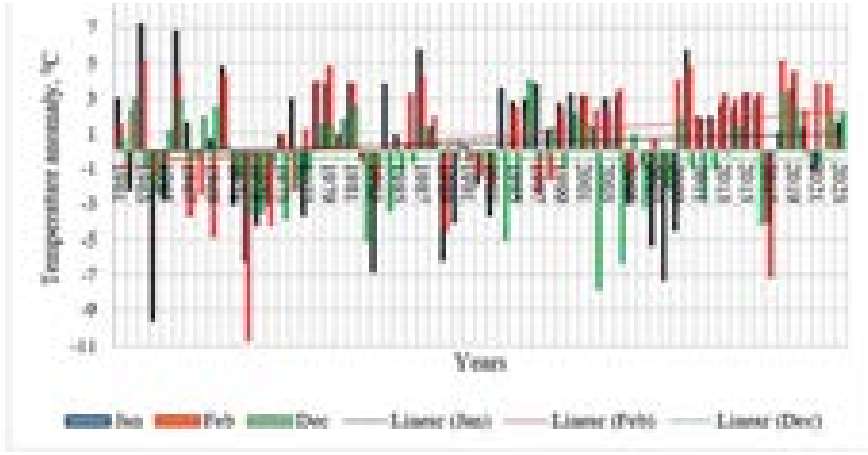


Fig. 3. Time variation trend in the mean monthly minimum temperature anomalies in winter season on the Nakhchivan AR

AR occurred in 57% of December, 69% of January, and 57% of February, with negative anomalies at 41%, 36%, and 41%, respectively. Between 1961 and 1992, negative anomalies were more frequent (December 54%, January 65%, February 69%), reflecting a pronounced winter warming trend of varying intensity. Positive anomalies were mostly concentrated in 1993–2023, and negative anomalies in 1961–1992.

Monthly mean minimum temperature anomalies in Nakhchivan AR show increasing trends only in January (0.17 °C/decade) and February (0.49 °C/decade), with the February trend statistically significant (Figure 3, Table 4).

Figure 3 shows that positive winter minimum temperature anomalies in Nakhchivan AR occurred in 38% of December, 64% of January, and 63% of February, while negative anomalies occurred in 60%, 33%, and 38%, respectively. Between 1961 and 1992, negative anomalies were more frequent (December 45%, January and February 67%), reflecting a variable increase in January and February minima. Most large positive anomalies were recorded during 1993–2023.

Comparative analysis indicates that January maximum temperature anomalies increased 2.7 times, and February 1.9 times, more than minimum anomalies, suggesting that winter warming is primarily driven by faster daytime temperature rises.

Spring monthly mean maximum and minimum temperature anomalies in Nakhchivan AR (relative to 1961–1990) show significant warming in all spring months, with the fastest increase in March (0.59 °C/decade) and the slowest in May (0.30 °C/decade) (Figures 4–5, Table 4).

Positive spring maximum temperature anomalies in Nakhchivan AR occurred in 63% of March, 60% of April, and 57% of May, with negative anomalies at 37%, 40%, and 40%, respectively. Between 1961 and 1992, negative anomalies were more frequent (March 74%, April 64%, May 69%), indicating a variable increase in spring maxima. Positive anomalies were concentrated in 1993–2023,

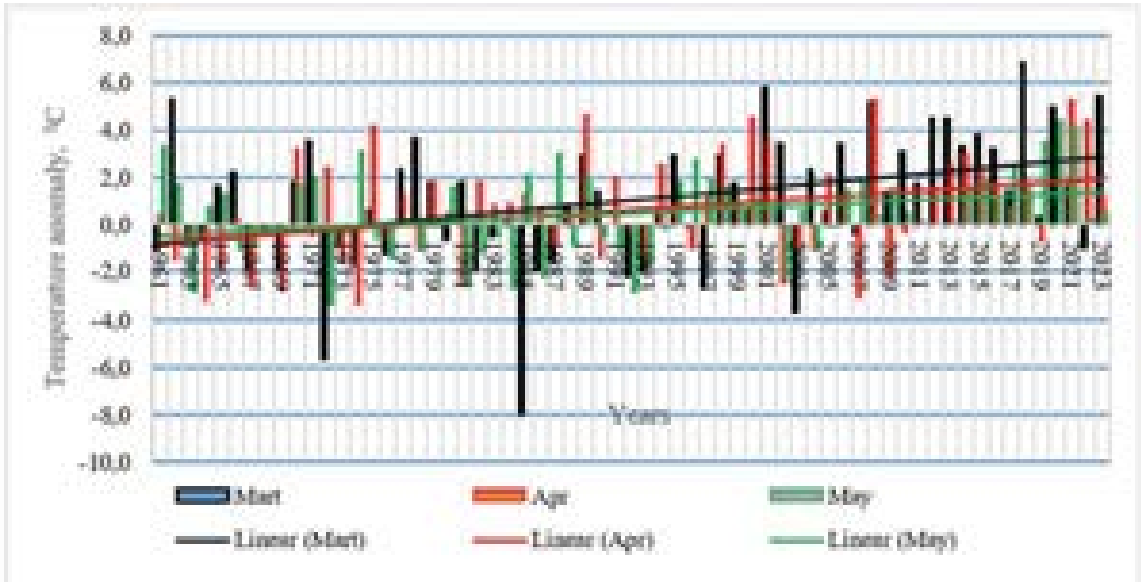


Fig. 4. Time variation trend in the mean monthly maximum temperature anomalies in spring season on the Nakhchivan AR

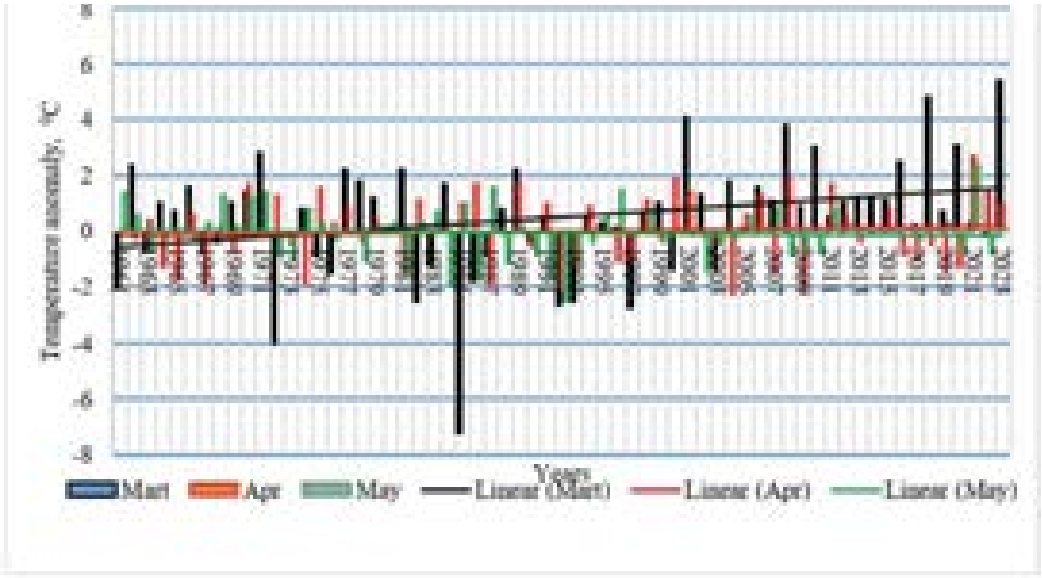


Fig. 5. Time variation trend in the meanmonthly minimum temperature anomalies in spring season on the Nakhchivan AR

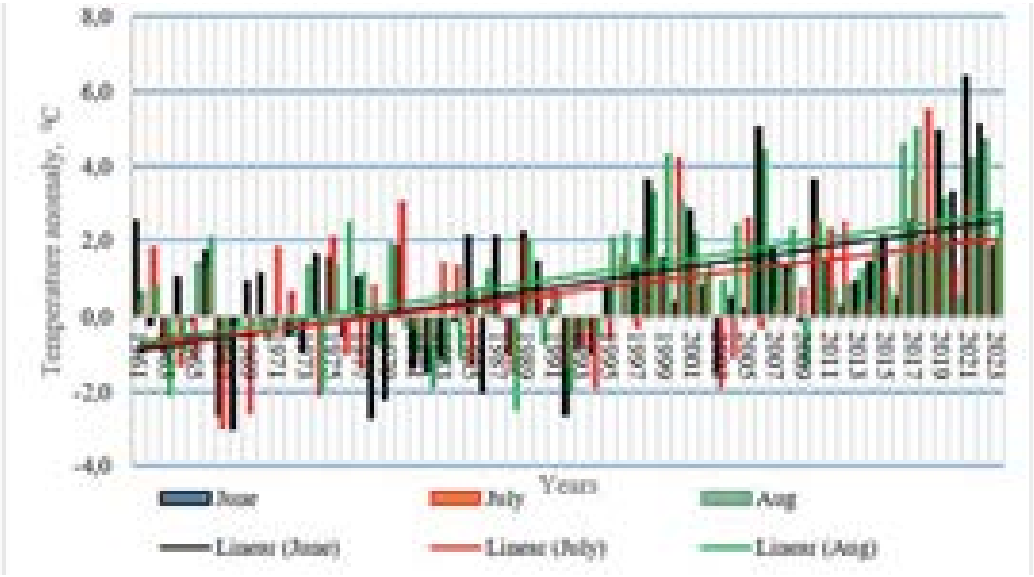


Fig. 6. Time variation trend in the meanmonthly maximum temperature anomalies in summer season on the Nakhchivan AR

while negative anomalies dominated 1961–1992 (Figure 4).

Spring monthly mean minimum temperature anomalies in Nakhchivan AR showed a significant upward trend in March (0.34 °C/decade), a weaker increase in April (0.06 °C/decade), and a non-significant decrease in May (−0.03 °C/decade) (Table 4). Positive anomalies occurred in 68% of March, 44% of April, and 46% of May, while negative anomalies dominated 32%, 51%, and 49% of years, respectively. Between 1961 and 1992, negative anomalies were more frequent, indicating the strongest minimum temperature increase in March. Positive anomalies were concentrated in 1993–2023 (Figure 5).

Comparative analysis indicates that March maximum temperature anomalies increased 1.7 times, and April anomalies 7.1 times, more than minimum anomalies, suggesting that spring warming is mainly driven by faster daytime temperature rises.

Summer monthly mean maximum and minimum temperature anomalies in Nakhchivan AR show significant warming in all months, with the fastest increase in June and August (0.55 °C/decade) and the slowest in July (0.46 °C/decade) (Figures 6–7, Table 4).

Positive summer maximum temperature anomalies in Nakhchivan AR occurred in 65% of June, 62% of July, and 67% of August, with negative anomalies at 40%, 35%, and 35%, respectively. Between 1961 and 1992, negative anomalies were more frequent (June 82%, July 68%, August 86%), indicating a variable increase in summer maxima. Positive anomalies were mainly recorded in 1993–2023, and negative anomalies in 1961–1992 (Figure 6).

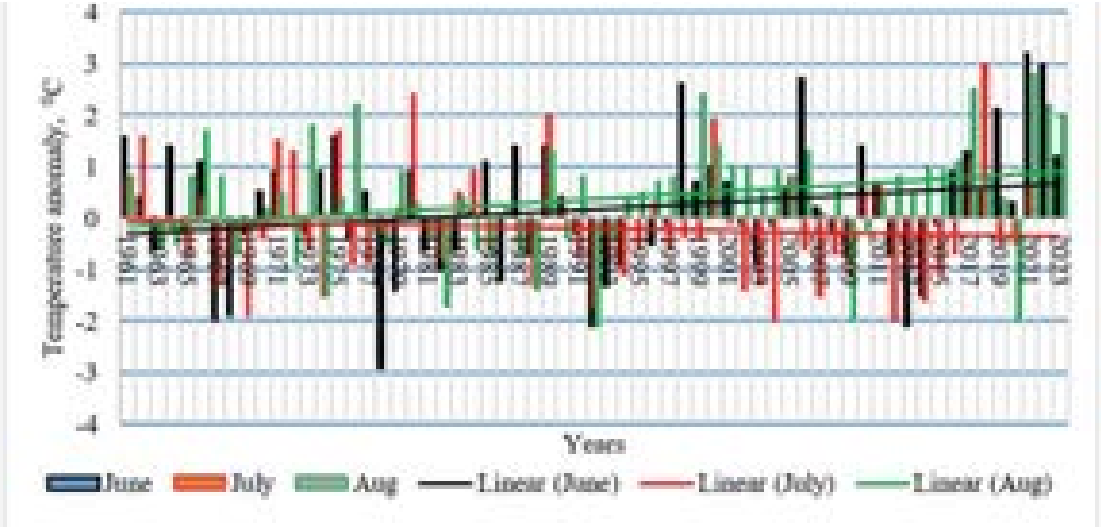


Fig. 7. Time variation trend in the mean monthly minimum temperature anomalies in summer season on the Nakhchivan AR

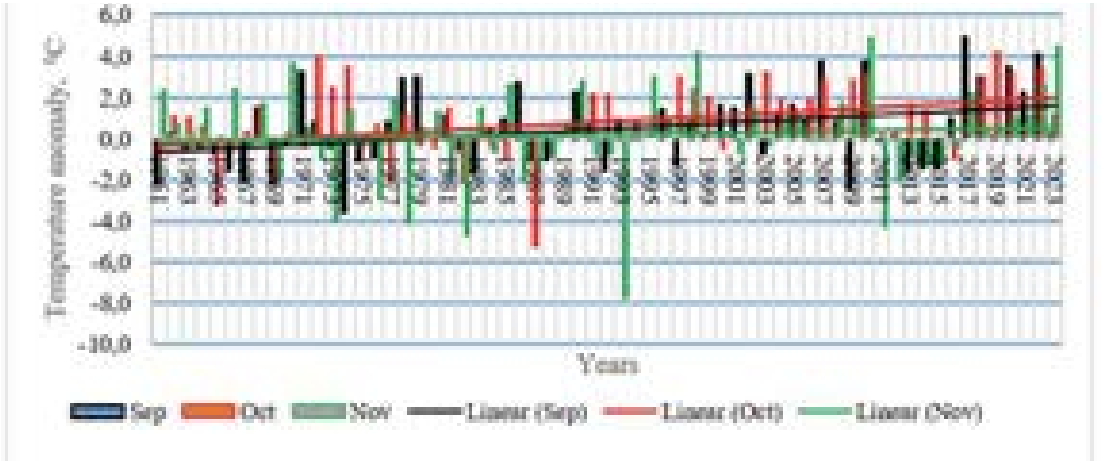


Fig. 8. Time variation trend in the meanmonthly maximum temperature anomalies in autumn season on the Nakhchivan AR

Summer monthly mean minimum temperature anomalies in Nakhchivan AR increased significantly only in August (0.17 °C/decade), rose slightly in June (0.16 °C/decade), and declined non-significantly in July (−0.05 °C/decade) (Table 2). Positive anomalies occurred in 51% of June, 33% of July, and 67% of August, while negative anomalies dominated 46%, 64%, and 33% of years. Between 1961 and 1992, negative anomalies were more frequent, indicating the strongest increase in August minima. Positive anomalies were concentrated in 1993–2023, while roughly half of the negative anomalies occurred in 1961–1992 (Figure 7).

Comparative analysis indicates that June and August maximum temperature anomalies increased 3.3 times more than minima, suggesting that summer warming, like winter and spring, is primarily driven by faster daytime temperature rises.

Autumn monthly mean maximum and minimum temperature anomalies in Nakhchivan AR show increasing trends in all months, with the fastest and statistically significant rises in September (0.36 °C/decade) and October (0.37 °C/decade), and a slower, non-significant increase in November (0.12 °C/decade) (Figure 8, Table 4).

In Nakhchivan AR, positive autumn maximum temperature anomalies occurred in 60% of September, 75% of October, and 57% of November, while negative anomalies occurred in 38%, 25%, and 43% of years. Between 1961 and 1992, negative anomalies were more frequent (September 71%, October 88%, November 56%), indicating variable warming intensity. Positive anomalies were mainly observed in 1993–2023, and negative anomalies in 1961–1992 (Figure 8).

Autumn monthly mean minimum temperature anomalies in Nakhchivan AR increased significantly in September (0.27 °C/decade), rose non-significantly in October (0.15 °C/decade), and slightly declined in November (−0.02 °C/decade) (Table 4). Positive anomalies occurred in 65% of September, 54% of October, and 44% of November, while negative anomalies dominated 29%, 41%, and 33% of years. Between 1961 and 1992, negative anomalies were more frequent, indicating the strongest increase in September minima. Positive anomalies were concentrated in 1993–2023, while

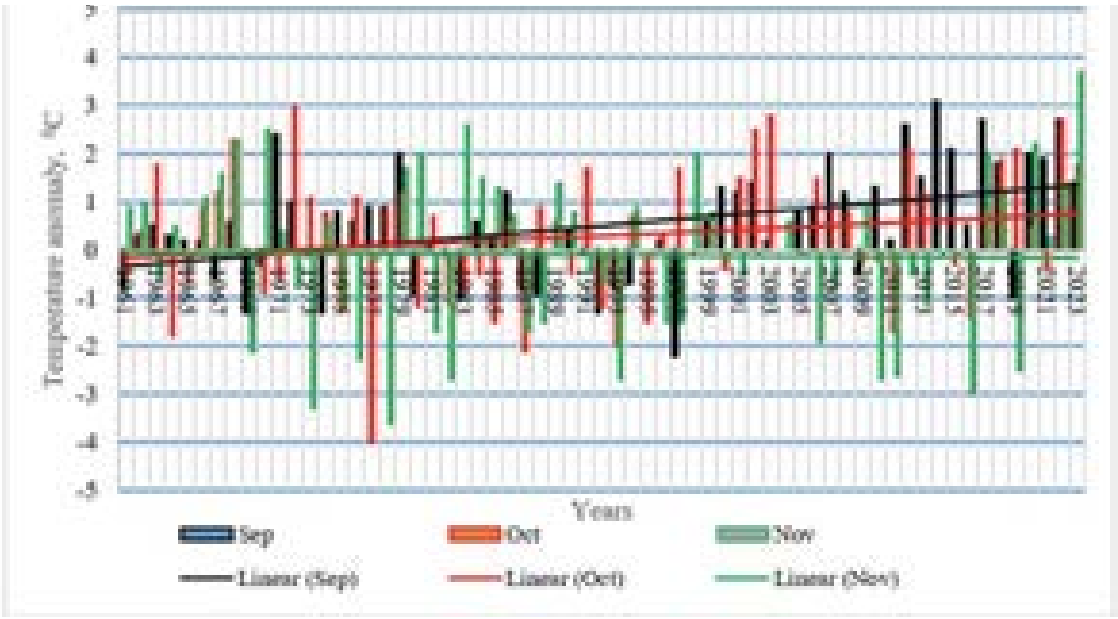


Fig. 9. Time variation trend in the meanmonthly minimum temperature anomalies in autumn season on the Nakhchivan AR

negative anomalies mostly occurred in 1961–1992 (Figure 9).

Comparative analysis shows that September maximum temperature anomalies increased 1.3 times, and October anomalies 2.5 times, more than minima, indicating that autumn warming, like in other seasons, is mainly driven by faster daytime temperature rises.

Temporal Variability of Maximum Temperature Anomaly Trends

Table 5 summarizes the monthly rates of change in maximum temperature anomalies (ΔTmax) across 30-year intervals and selected periods, while Table 6 presents the corresponding Pearson correlation coefficients, indicating the consistency and variability of temporal trends.

During 1961–2023, the strongest winter warming occurred in February at all stations, with statistically significant rates ranging from 0.58 to 1.18 °C/decade ($r > 0.24$). In January, significant warming was detected only at Ordubad and Sharur (0.61–0.64 °C decade/), while December trends were not significant (Tables 5–6).

During the **spring months**, statistically significant warming in maximum temperature was observed at all stations, except for May in Nakhchivan. The warming rates ranged from 0.38 to 0.78 °C/decade in March, 0.34 to 0.54 °C/decade in April, and 0.01 to 0.40 °C/decade in May.

During **autumn,** maximum temperature increased at all stations, with rates of 0.13–0.68 °C/decade in September, 0.14–0.52 °C/decade in October, and 0.02–0.31 °C/decade in November;

Table 5

The rates of change in monthly mean maximum temperature anomalies (°C/decades) for the meteorological stations across different climatic periods.

Station	Periods	Number of month											
		01	02	03	04	05	06	07	08	09	10	11	12
Ordubad	1961-2023	0.61	0.89	0.55	0.44	0.36	0.80	1.12	1.10	0.68	0.52	0.24	0.27
	1971-2023	0.83	1.11	0.76	0.22	0.45	0.93	1.10	1.18	0.49	0.37	0.46	0.59
	1981-2023	0.66	1.06	1.13	0.23	0.61	1.15	1.50	1.56	0.58	0.75	0.61	0.73
	1991-2023	0.87	1.18	1.19	0.51	0.68	1.59	2.09	1.63	0.82	0.40	0.79	0.98
Julfa	1961-2023	0.37	1.07	0.78	0.54	0.51	0.39	0.40	0.73	0.48	0.45	0.31	0.40
	1971-2023	0.73	1.46	1.15	0.46	0.79	0.57	0.45	0.98	0.44	0.48	0.69	0.90
	1981-2023	0.71	1.53	1.74	0.65	1.26	0.81	0.73	1.36	0.67	0.86	0.93	1.31
	1991-2023	1.00	1.52	1.84	0.86	1.71	1.02	0.98	1.16	0.98	0.55	1.04	1.78
Nakhchivan	1961-2023	0.30	0.89	0.63	0.35	0.10	0.42	0.18	0.29	0.21	0.14	0.07	0.01
	1971-2023	0.67	1.34	0.99	0.29	0.32	0.68	0.22	0.45	0.15	0.17	0.26	0.34
	1981-2023	0.46	1.22	1.47	0.43	0.67	1.02	0.44	0.81	0.43	0.51	0.35	0.77
	1991-2023	0.50	1.41	1.50	0.49	0.71	1.23	0.65	0.51	0.39	0.01	0.55	1.00

Продовження Таблиці 5 / Continuation Table 5

Şahbuz	1961-2023	0.39	0.58	0.38	0.34	0.29	0.66	0.43	0.27	0.13	0.39	0.02	0.17
	1971-2023	0.60	0.82	0.55	0.19	0.42	0.84	0.41	0.26	-.03	0.38	0.17	0.48
	1981-2023	0.21	0.75	0.69	-.06	0.42	0.90	0.47	0.35	0.02	0.58	0.03	0.69
	1991-2023	0.03	0.77	0.49	-.12	0.41	1.09	0.65	-.06	-.09	-.00	-.06	0.60
Şharur	1961-2023	0.64	1.18	0.60	0.47	0.25	0.46	0.17	0.38	0.34	0.33	0.13	0.22
	1971-2023	0.92	1.58	0.88	0.45	0.45	0.66	0.21	0.46	0.34	0.48	0.51	0.65
	1981-2023	0.74	1.43	1.11	0.42	0.55	0.87	0.28	0.59	0.41	0.69	0.44	0.79
	1991-2023	1.01	1.73	1.02	0.46	0.60	1.23	0.50	0.22	0.57	0.24	0.50	1.15

Table 6

The Pearson correlation coefficients for the trends of monthly mean maximum temperature anomalies in the Nakhchivan AR over different climatic periods (10-year intervals). Significance expressed as (bold font) p < 0.05

Station	Periods	Number of month											
		01	02	03	04	05	06	07	08	09	10	11	12
Ordubad	1961-2023	**0.28**	**0.44**	**0.38**	**0.34**	**0.33**	**0.64**	**0.76**	**0.72**	**0.52**	**0.43**	0.20	0.16
	1971-2023	**0.34**	**0.48**	**0.42**	0.15	**0.35**	**0.63**	**0.69**	**0.68**	**0.35**	**0.27**	**0.28**	**0.27**
	1981-2023	0.23	**0.40**	**0.51**	0.12	**0.38**	**0.64**	**0.75**	**0.70**	**0.34**	**0.45**	**0.39**	0.26
	1991-2023	0.24	0.33	**0.45**	0.20	**0.35**	**0.66**	**0.80**	**0.60**	**0.35**	0.21	0.28	0.27
Julfa	1961-2023	0.16	**0.45**	**0.43**	**0.42**	**0.37**	**0.33**	**0.38**	**0.60**	**0.43**	**0.37**	0.23	0.20
	1971-2023	**0.28**	**0.54**	**0.52**	**0.31**	**0.46**	**0.38**	**0.36**	**0.64**	**0.33**	**0.33**	**0.42**	**0.37**
	1981-2023	0.23	**0.50**	**0.61**	**0.35**	**0.56**	**0.42**	**0.45**	**0.70**	**0.41**	**0.47**	**0.46**	**0.40**
	1991-2023	0.26	**0.38**	**0.54**	**0.34**	**0.57**	**0.39**	**0.44**	**0.52**	**0.43**	0.26	**0.40**	**0.42**
Nakhchivan	1961-2023	0.13	**0.36**	**0.35**	**0.30**	0.10	**0.37**	0.21	**0.32**	0.20	0.15	0.01	0.00
	1971-2023	0.26	**0.48**	**0.43**	0.21	0.26	**0.50**	0.21	**0.40**	0.12	0.15	0.17	0.15
	1981-2023	0.15	**0.40**	**0.51**	0.25	**0.46**	**0.60**	**0.35**	**0.55**	0.28	**0.37**	0.18	0.26
	1991-2023	0.14	**0.35**	**0.42**	0.22	**0.39**	**0.56**	**0.38**	0.30	0.20	-0.02	0.23	0.26
Şahbuz	1961-2023	0.20	**0.33**	**0.26**	**0.28**	**0.30**	**0.56**	**0.46**	**0.26**	0.12	**0.35**	0.02	0.10
	1971-2023	**0.28**	**0.42**	**0.30**	0.13	**0.36**	**0.60**	**0.39**	0.22	-0.02	**0.29**	0.11	0.23
	1981-2023	0.09	**0.36**	**0.30**	-0.03	**0.31**	**0.54**	**0.36**	0.21	0.01	**0.35**	0.02	0.26
	1991-2023	0.00	0.28	0.17	-0.05	0.25	0.51	**0.39**	-0.02	-0.04	0.00	-.02	0.18
Şharur	1961-2023	**0.26**	**0.47**	**0.38**	**0.37**	**0.25**	**0.40**	0.18	**0.39**	**0.36**	**0.35**	0.09	0.12
	1971-2023	**0.32**	**0.54**	**0.45**	**0.30**	**0.38**	**0.47**	0.18	**0.39**	**0.30**	**0.41**	**0.30**	**0.29**
	1981-2023	0.21	**0.45**	**0.47**	0.23	**0.37**	**0.49**	0.19	**0.39**	**0.30**	**0.50**	0.22	0.27
	1991-2023	0.22	**0.41**	**0.38**	0.19	0.33	**0.51**	0.24	0.11	0.30	0.17	0.18	0.30

however, statistically significant trends were limited to Ordubad (September–October), Julfa and Sharur (September), Shahbuz (October).

The results summarized in Table 7 show a consistent increase in maximum temperatures across all months, seasons, and annually during 1961–2023. Statistically significant warming was observed in 47% of winter cases, 93% in spring, 87% in summer, 47% in autumn, and 68% annually, indicating that the strongest significant increases occurred in spring and summer.

For the subsequent climatic periods (1971–2023, 1981–2023, 1991–2023), generalized trends in maximum temperature anomalies (Tmax) were as follows.

1) **1971–2023:** Warming signals strengthened and persisted in winter and autumn, whereas spring and summer exhibited relatively weaker warming.

2) **1981–2023:** Weaker warming was observed in winter, spring, and autumn, as well as annually, while summer showed a relatively stronger warming trend.

3) **1991–2023:** Winter warming occurred in all months, with significance in 27% of cases. Spring and summer warming affected 93% of months, with 53% and 73% statistically significant, respectively. Autumn warming occurred in 80% of months (20% cooling), but only 20% was significant. Annually, warming prevailed in 92% of years (8% cooling), with 43% reaching statistical significance.

4) Across all periods, winter warming was persistent, with statistically significant cases increasing from 47% to 73% before declining to 27%

Table 7

Generalized table of positive and negative values of the rates of maximum temperature anomalies and the recurrence of cases of their observation (in %) in the territory of Nakhchivan AR for different climatic periods, seasons and years. Recurrence of months showing warming or cooling in the numerator, recurrence of months with statistically significant warming or cooling in the denominator

Periods	Winter		Spring		Summer		Autumn		Year	
	war-ming	coo-ling	war-ming	cool-ing	war-ming	cool-ing	war-ming	coo-ling	warm-ing	cool-ing
1961-2023	100/47	0/0	100/93	0/0	100/87	0/0	100/47	0/0	100/68	0/0
1971-2023	100/73	0/0	100/73	0/0	100/80	0/0	93/80	0/0	98/77	0/0
1981-2023	100/47	0/0	93/60	7/0	100/87	0/0	100/67	0/0	98/65	2/0
1991-2023	100/27	0/0	93/53	7/0	93/73	7/0	80/20	20/0	92/43	8/0

in 1991–2023. Spring warming occurred in nearly all months (93–100%), although significance decreased from 93% to 53%. Summer warming was widespread (93–100%) and consistently highly significant (73–87%). Autumn warming was more variable, with peak significance (80%) in 1971–2023. Annually, warming affected 92–100% of years, with statistical significance ranging from 43% to 77%.

These results demonstrate that warming trends are seasonally and temporally variable, with spring and summer exhibiting the most consistently significant increases.

Temporal Variability of Minimum Temperature Anomaly Trends

Table 8 summarizes monthly trends in minimum temperature (ΔTmin) anomalies, with corresponding Pearson correlation coefficients shown in Table 9. During 1961–2023, **winter** warming was strongest in February at all stations (0.42–0.97 °C/decade), with statistically significant increases at Ordubad, Julfa, and Sharur. January trends were positive but not significant (0.34–0.66 °C/decade), while December exhibited non-significant cooling or weak warming depending on the station.

Table 8

The rates of change in monthly mean minimum temperature anomalies (°C/decades) for the meteorological stations across different climatic periods

Station	Periods	Number of month											
		01	02	03	04	05	06	07	08	09	10	11	12
Ordubad	1961-2023	0.34	0.42	0.44	0.23	0.24	0.56	0.38	0.58	0.68	0.23	0.16	-.02
	1971-2023	0.60	0.69	0.68	0.18	0.37	0.58	0.22	0.53	0.66	0.26	0.44	0.33
	1981-2023	0.51	0.65	1.09	0.34	0.65	0.90	0.47	0.83	1.06	0.54	0.56	0.37
	1991-2023	0.40	0.92	1.22	0.49	0.87	1.28	0.74	0.80	1.42	0.41	0.86	0.57
Julfa	1961-2023	0.35	0.69	0.40	0.21	0.05	0.23	0.01	0.34	0.63	0.50	0.32	0.15
	1971-2023	0.45	0.94	0.65	0.18	0.11	0.25	-.04	0.45	0.73	0.65	0.49	0.38
	1981-2023	0.34	0.90	1.03	0.23	0.17	0.24	0.00	0.59	0.97	0.75	0.45	0.33
	1991-2023	0.12	1.13	1.20	0.40	0.27	0.41	0.16	0.50	1.41	0.90	0.91	0.51
Nakhchivan	1961-2023	-.07	0.40	0.22	-.20	-.28	-.05	-.37	-.13	-.10	-.11	-.22	-.20
	1971-2023	0.14	0.72	0.46	-.22	-.17	0.13	-.28	0.09	0.00	0.02	-.07	0.05
	1981-2023	0.05	0.69	1.05	0.05	0.20	0.57	0.13	0.62	0.65	0.46	0.09	0.31
	1991-2023	-.43	1.14	1.24	0.16	0.30	0.91	0.45	0.50	0.68	0.38	0.17	0.62
Şahbuz	1961-2023	-.12	0.23	0.19	-.18	-.25	-.03	-.27	-.10	-.16	-.23	-.27	-.03
	1971-2023	0.12	0.51	0.35	-.30	-.19	0.04	-.30	-.04	-.18	-.20	-.09	0.39
	1981-2023	-.30	0.34	0.57	-.43	-.19	0.08	-.23	0.13	0.00	-.16	-.24	0.38
	1991-2023	-.64	0.62	0.54	-.45	-.13	0.28	0.13	0.10	0.23	-.28	0.03	0.73
Şharur	1961-2023	0.66	0.97	0.60	0.18	0.19	0.17	-.04	0.22	0.32	0.46	0.07	0.40
	1971-2023	0.66	0.97	0.60	0.18	0.19	0.17	-.04	0.22	0.32	0.46	0.07	0.40
	1981-2023	0.25	0.58	0.74	0.00	0.06	0.02	-.23	-.07	0.26	0.35	-.23	0.20
	1991-2023	0.19	1.16	0.91	0.17	0.08	0.04	-.10	-.36	0.46	0.21	0.02	0.63

Table 9

The Pearson correlation coefficients for the trends of monthly mean minimum temperature anomalies in the Nakhchivan AR over different climatic periods (10-year intervals). Significance expressed as (bold font) p < 0.05

Station	Periods	Number of month											
		01	02	03	04	05	06	07	08	09	10	11	12
Ordubad	1961-2023	0.18	**0.26**	**0.37**	**0.26**	**0.28**	**0.56**	**0.42**	**0.62**	**0.65**	0.23	0.18	-0.01
	1971-2023	**0.30**	**0.37**	**0.45**	0.16	**0.35**	**0.50**	0.21	**0.50**	**0.54**	0.21	**0.41**	0.21
	1981-2023	0.21	**0.31**	**0.57**	0.23	**0.48**	**0.65**	**0.37**	**0.60**	**0.70**	**0.38**	**0.44**	0.18
	1991-2023	0.14	0.33	**0.53**	0.25	**0.50**	**0.69**	**0.41**	**0.46**	**0.69**	0.22	**0.54**	0.21
Julfa	1961-2023	0.17	**0.41**	**0.34**	0.23	0.06	0.23	0.02	**0.45**	**0.58**	**0.35**	**0.27**	0.11
	1971-2023	0.21	**0.49**	**0.44**	0.17	0.12	0.20	-0.04	**0.49**	**0.56**	**0.37**	**0.35**	0.23
	1981-2023	0.13	**0.44**	**0.55**	0.16	0.15	0.15	0.00	**0.50**	**0.58**	**0.33**	0.26	0.16
	1991-2023	0.03	**0.42**	**0.56**	0.21	0.17	0.19	0.12	0.33	**0.60**	0.28	**0.38**	0.18
Nakhchivan	1961-2023	-0.03	0.21	0.16	**0.28**	**-0.40**	-0.06	**-0.43**	-0.15	-0.13	-0.12	-0.22	-0.13
	1971-2023	0.05	**0.32**	**0.27**	-0.25	-0.21	0.13	**-0.29**	0.08	0.00	0.02	-0.06	0.03
	1981-2023	0.01	0.29	**0.48**	0.05	0.22	**0.50**	0.12	**0.50**	**0.69**	**0.38**	0.06	0.14
	1991-2023	-0.10	**0.38**	**0.50**	0.12	0.26	**0.56**	0.33	0.33	**0.59**	0.24	0.09	0.20
Şahbuz	1961-2023	-0.05	0.13	0.17	-0.23	**-0.39**	-0.04	**-0.32**	-0.15	-0.23	**-0.28**	-0.23	-0.02
	1971-2023	0.05	0.24	0.26	**-0.30**	-0.26	0.05	**-0.29**	-0.05	-0.21	-0.21	-0.06	-0.20
	1981-2023	-0.09	0.15	**0.33**	**-0.33**	-0.20	0.07	-0.18	0.13	0.00	-0.15	-0.14	0.15
	1991-2023	-0.15	0.20	0.29	-0.27	-0.11	0.20	0.08	0.07	0.17	0.19	0.01	0.22
Şarur	1961-2023	0.17	**0.34**	**0.36**	**0.32**	0.18	0.19	-0.02	**0.30**	**0.53**	**0.38**	-0.04	0.02
	1971-2023	0.24	**0.39**	**0.40**	0.21	0.30	0.20	-0.04	**0.28**	**0.49**	**0.43**	0.05	0.22
	1981-2023	0.08	0.23	**0.40**	0.00	0.07	0.01	-0.19	-0.08	**0.34**	**0.30**	-0.15	0.09
	1991-2023	0.05	**0.35**	**0.44**	0.12	0.08	0.03	-0.06	-0.30	**0.45**	0.14	0.01	0.20

In spring, Tmin exhibited statistically significant warming at Ordubad in all months (0.23–0.44°C/decade), at Julfa in March (0.40°C/decade), at Sharur in March (0.60°C/decade) and April (0.18°C/decade). By contrast, March warming was non-significant in Nakhchivan and Sharur, while April–May cooling occurred, with significant decreases in Nakhchivan (April: −0.20°C/decade) and Shahbuz (May: −0.25°C/decade).

During **summer**, Tmin increased significantly in Ordubad (0.38–0.58 °C/decade), with similar trends in Julfa and Sharur in August. In contrast, Nakhchivan (−0.37 °C/decade) and Shahbuz (−0.27 °C/decade) showed decreasing Tmin trends, with the July declines being statistically significant.

In **autumn**, Tmin showed positive trends in Ordubad, Julfa, and Sharur, and negative trends in Nakhchivan and Shahbuz. Statistically significant warming occurred in Ordubad (September: 0.68 °C/decade), Julfa (all months: 0.32–0.63 °C/decade), and Sharur (September: 0.32 °C/decade; October: 0.46 °C/decade), while significant cooling was observed only in Shahbuz in October (−0.23 °C/decade).

Similar to the Tmax anomalies, for subsequent climatic periods, a series of generalized results were obtained regarding the trend changes in Tmin time series (noting that these trend variations are described by the values presented in Tables 8 and 9) (see Table 10).

1)For 1971–2023, Tmin anomalies indicate continuous winter warming (100%), with 33% statistically significant. Spring warming occurred in 73% of months, though significant cases declined from 47% to 33%, with 27% non-significant cooling. Summer warming rose from 53% to 67%, while significance dropped from 33% to 20%; autumn followed a similar pattern. Annually, warming increased, but significant events nearly halved, and cooling decreased from 37% to 23% without significance, indicating that shorter analysis periods amplify apparent warming trends.

2)For 1981–2023, Tmin trends showed seasonal modulation: winter warming weakened (20% significant, 20% cooling), spring warming increased (40% significant, 7% cooling), and summer–autumn warming rose (60% significant). Annually, warming frequency was stable, with significant warming increasing from 23% to 53% and significant cooling from 0% to 13%.

3) For 1991–2023, Tmin trends showed winter warming in 87% of cases (20% significant) and 13% cooling. Spring warming also affected 87% of months, with fewer significant events. Annually, warming dominated (88%) versus 15% cooling, with 30% of warming and 2% of cooling statistically significant.

Table 10

Generalized table of positive and negative values of the rates of minimum temperature anomalies and the recurrence of cases of their observation (in %) in the territory of Nakhchivan AR for different climatic periods, seasons and years. Recurrence of months showing warming or cooling in the numerator, recurrence of months with statistically significant warming or cooling in the denominator

Periods	Winter		Spring		Summer		Autumn		Year	
	war-ming	coo-ling	war-ming	cool-ing	war-ming	cool-ing	war-ming	coo-ling	warm-ing	cool-ing
1961-2023	67/20	33/0	73/47	27/13	53/33	47/13	60/40	40/7	63/42	37/8
1971-2023	100/33	0/0	73/33	27/0	67/20	33/7	67/53	33/0	77/23	23/0
1981-2023	80/20	20/0	87/40	13/7	80/60	20/0	80/67	20/0	77/53	18/13
1991-2023	87/20	13/0	87/33	13/0	87/27	13/0	93/40	7/0	88/30	15/2

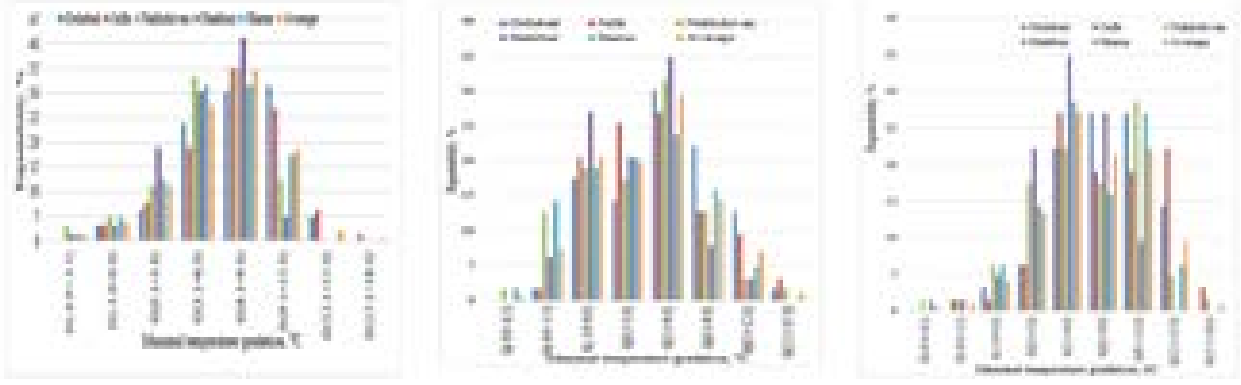
Assessment of the Frequency of Occurrence of Maximum Air Temperature Across Different Gradations

Monthly maximum temperatures in Nakhchivan AR (1961–2023) were analyzed using 3 °C intervals from −9.0 °C to 42.0 °C. For each of the five stations, the number and percentage of observations within each gradation were calculated, averaged across stations, and then compiled for the entire region. The results are presented graphically.

The frequency of occurrence of different maximum temperature gradations during the **winter months** in the Nakhchivan AR is illustrated in Figure 10.

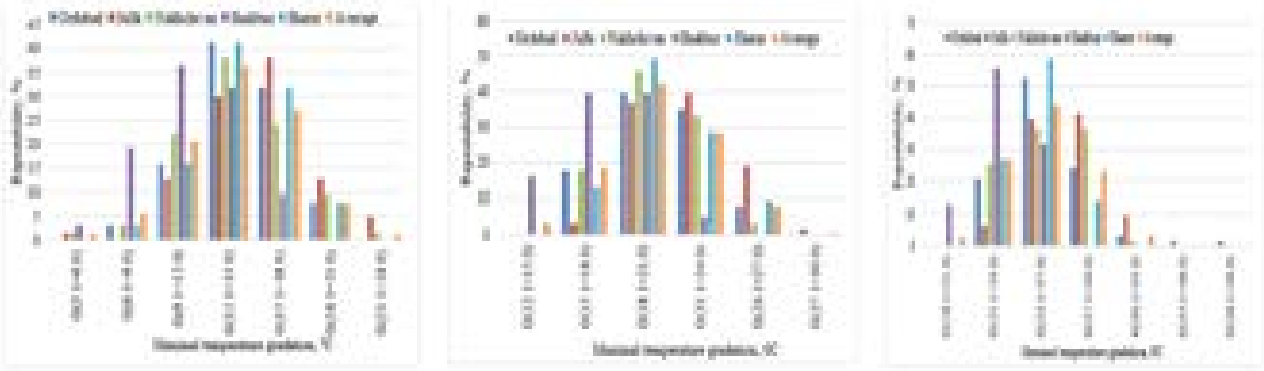
Monthly maximum temperature distributions in Nakhchivan AR exhibited clear spatial patterns. In December, −6.0 to −3.1 °C occurred at Nakhchivan, Shahbuz, and Sharur (1.6–3.2%), 12.1–15.0 °C at Ordubad, Julfa, and Sharur (2.2–6.3%), and 15.1–18.0 °C only at Julfa (1.6%), with 6.1–9.0 °C most frequent; temperatures spanned eight intervals (Figure 10). In January, the coldest maxima (−9.0 to −6.1 °C) appeared at Nakhchivan and Sharur (1.6%), the warmest (12.1–15.0 °C) at Ordubad, Julfa, and Nakhchivan (1.6–3.2%), and 3.1–6.0 °C was most frequent (23.8–34.9%), across eight intervals. In February, −9.0 to −6.1 °C occurred only at Nakhchivan (1.6%), −6.0 to −3.1 °C at Julfa, Nakhchivan, and Shahbuz (1.6% each), and 15.1–18.0 °C at Julfa and Nakhchivan (1.6–3.2%), with 3.1–6.0 °C most frequent (22.2–34.9%); temperatures spanned nine intervals.

In March, negative maxima were absent, 21.1–24.0 °C occurred at Julfa and Nakhchivan (4.8%), Shahbuz did not exceed 18.1–21.0 °C, and 12.1–15.0 °C was most frequent (30.2–41.7%), spanning seven intervals (Figure 11). In April, rapid warming was evident, with most stations showing maximum temperatures of 15.1–18.0 °C and peak values reaching 24.1–27.0 °C. At Shahbuz, 15.1–21.0 °C was most frequent (39.7%), while other stations were dominated by 18.1–24.0 °C (28.6–49.2%); temperatures spanned six intervals. In May, Shahbuz maxima were mostly 18.1–27.0 °C (13–55.6%), Julfa reached 33.1–39.0 °C (1.6%), and other stations were dominated by 24.1–27.0 °C (36.5–58.7%), with seven intervals overall reflecting rapid warming.



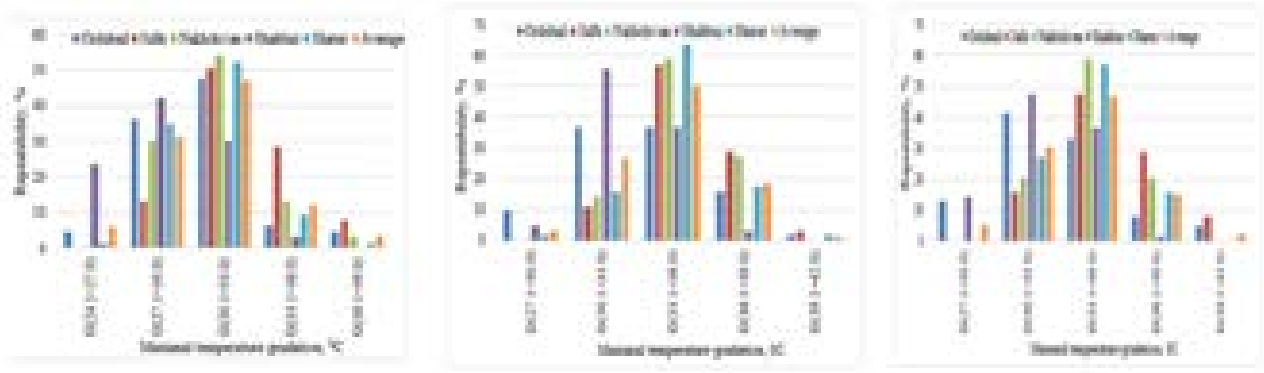
December January February

Fig. 10. Repetition of average monthly maximum air temperatures in Nakhchivan AR during winter months in different gradations



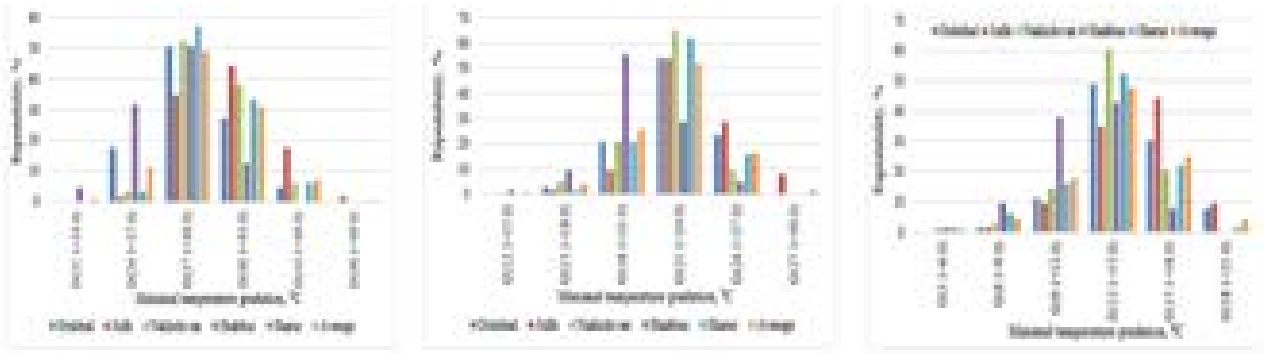
March April May

Fig. 11. Repetition of average monthly maximum air temperatures in Nakhchivan AR during spring months in different gradations



June July August

Fig. 12. Repetition of average monthly maximum air temperatures in Nakhchivan AR during summer months in different gradations



September October November

Fig. 13. Repetition of average monthly maximum air temperatures in Nakhchivan AR during autumn months in different gradations

In July, maximum temperatures ranged from 27.1–30.0 °C at Ordubad, Shahbuz, and Sharur, and 30.1–33.0 °C at Julfa and Nakhchivan, with extreme values of 39.1–42.0 °C at Ordubad, Julfa, and Sharur. Shahbuz most frequently recorded 30.1–33.0 °C (55.6%), while other stations favored 33.1–36.0 °C (36.5–63.5%); five gradation intervals were observed (Figure 12). In August, maxima were 27.1–30.0 °C at Ordubad and Shahbuz, 30.1–33.0 °C at other stations, and 39.1–42.0 °C at Ordubad and Julfa. Most frequent gradations were 30.1–33.0 °C at Ordubad and Shahbuz, and 33.1–36.0 °C at Julfa, Nakhchivan, and Sharur; less frequent 36.1–39.0 °C occurred at Julfa and Nakhchivan. Overall, August maxima spanned five intervals (Figure 12).

In September, minimum maxima were 21.1–24.0 °C at Shahbuz and 24.1–27.0 °C at other stations, with highest values at Julfa (36.1–39.0 °C) and 33.1–36.0 °C elsewhere. The most frequent gradation, excluding Shahbuz, was 27.1–30.0 °C (44.4–57.1%); six intervals were observed (Figure 13). In October, minimum maxima were 12.1–15.0 °C at Shahbuz and 15.1–18.0 °C elsewhere, with peaks at Julfa (27.1–30.0 °C) and 24.1–27.0 °C at other stations. Most frequent gradations were 21.1–24.0 °C at Ordubad, Julfa, Nakhchivan, and Sharur, and 18.1–21.0 °C at Shahbuz; six intervals overall.

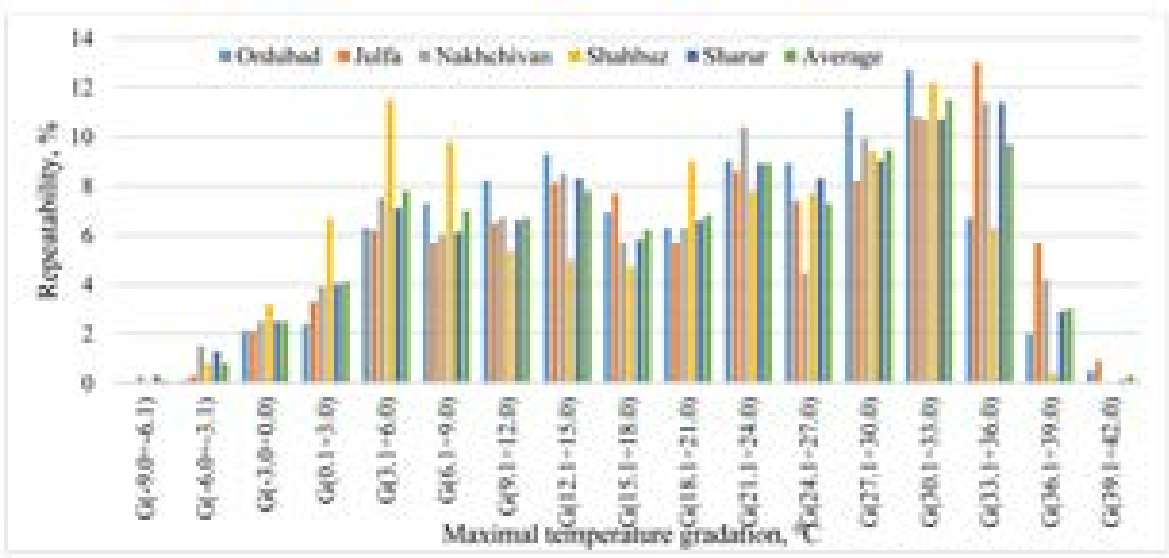


Fig. 14. Repetition of average monthly maximum air temperatures in the Nakhchivan AR in 1961-2023 years period in different gradations

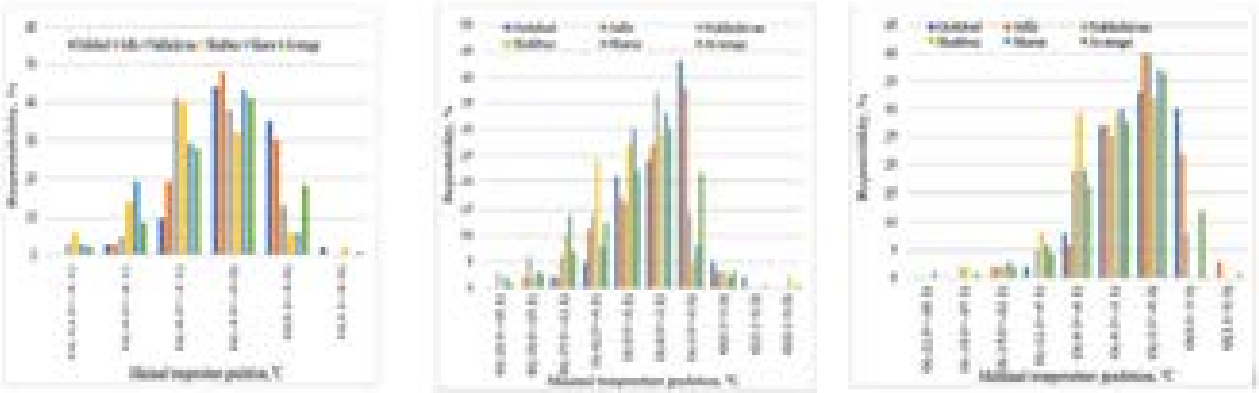
In November, minimum maxima were 3.1–6.0 °C at Nakhchivan, Shahbuz, and Sharur, 6.1–9.0 °C at Ordubad and Julfa, with highest values 18.1–21.0 °C at Ordubad and Julfa and 15.1–18.0 °C at other stations. Most frequent gradations were 12.1–15.0 °C at four stations and 15.1–18.0 °C at Julfa; six intervals overall.

Across all months and stations, maximum temperatures ranged from −9.0–6.1 °C to 39.1–42.0 °C, spanning 17 gradation intervals (Figure 14). At Shahbuz (~400 m higher), lower gradations (−3.0–0.0 °C to 18.1–21.0 °C) recurred 3.2–9.8%, while 30.1–33.0 °C reached 12.2%. At other stations, 30.1–33.0 °C was most frequent (10.7–12.7%).

Frequency Distribution of Minimum Air Temperatures in the Nakhchivan AR

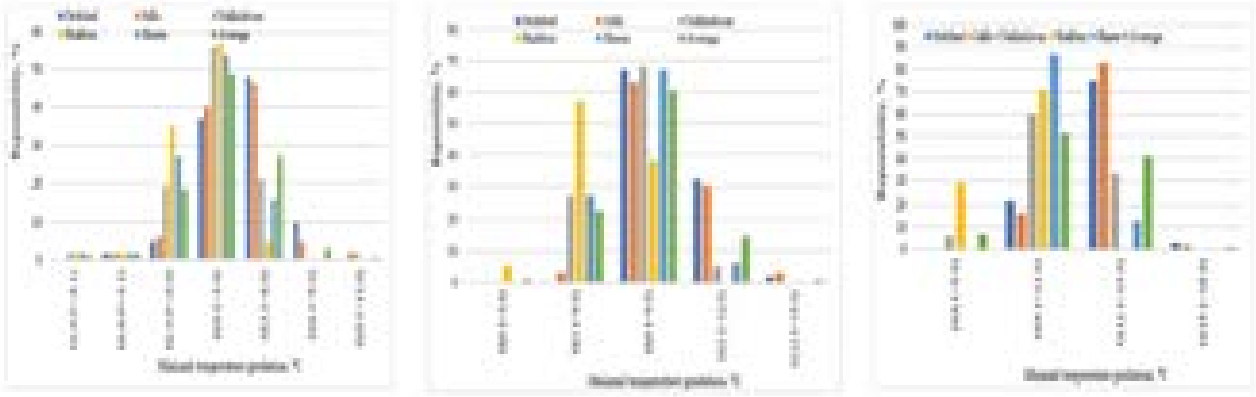
Monthly minimum temperatures in Nakhchivan AR (1961–2023) were analyzed using 3.0 °C intervals (−21.0 to 27.0 °C). Frequencies at five stations were normalized as relative recurrence (%), spatially averaged to represent regional conditions, and integrated across all classes. Results are presented graphically, with winter distributions shown in Figure 15.

In December, minimum temperatures in Nakhchivan AR ranged from −11.8 to 5.0 °C. The −12.0 to −9.1 °C class was infrequent at Nakhchivan, Shahbuz, and Sharur (3–4%), while 3.1–6.0 °C occurred only at Ordubad and Shahbuz (2%). The most frequent classes were −6.0 to −3.1 °C at Nakhchivan (41%) and Shahbuz (40%), and −3.0 to 0.0 °C at Ordubad, Julfa, and Sharur (43–48%); 0.1–3.0 °C was second most frequent at Ordubad and Julfa (30–35%), spanning six intervals. In January, −21.0 to −18.1 °C occurred at Nakhchivan (3%) and Sharur (26%), and 6.1–9.0 °C only at Shahbuz (2%). Most minima were −15.0 to −12.1 °C and 0.1–3.0 °C, with ten intervals overall. In February, −21.0 to −18.1 °C appeared only at Sharur (2%), 3.1–6.0 °C only at Julfa (3%), and −15.0 to 0.0 °C showed increasing recurrence, peaking at −3.0 to 0.0 °C (32–40%), across nine intervals (Figure 15).



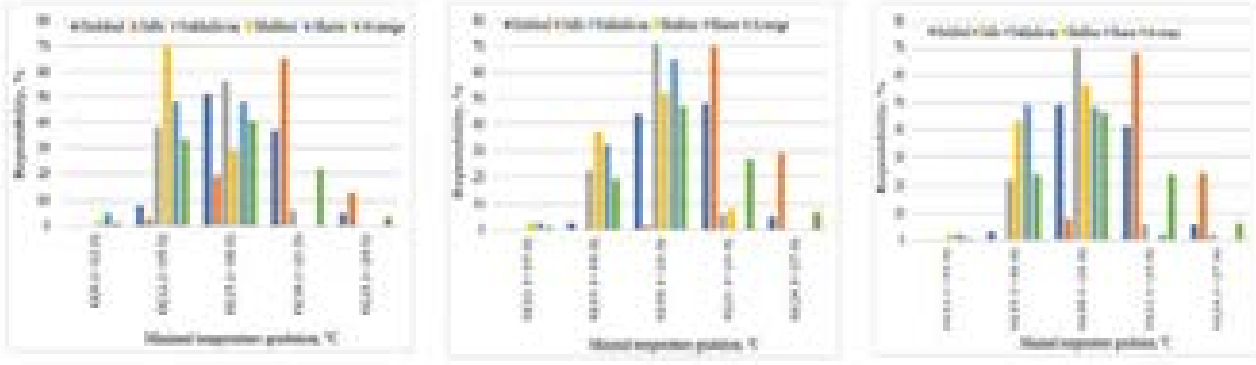
December **January** **February**

Fig. 15. Repetition of average monthly minimum air temperatures in Nakhchivan AR during winter months in different gradations



March April May

Fig. 16. Repetition of average monthly minimum air temperatures in Nakhchivan AR during spring months in different gradations



June July August

Fig. 17. Repetition of average monthly minimum air temperatures in Nakhchivan AR during summer months in different gradations

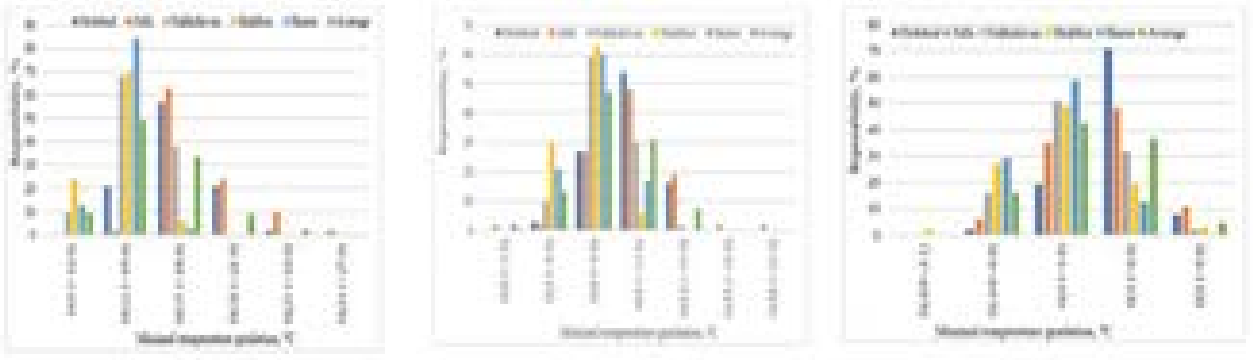
In March, negative minima (−9.0 to −3.1 °C) were rare (≤2%), with highest positive minima (9.1–12.0 °C) recorded infrequently at Nakhchivan, Julfa, and Ordubad. Dominant classes were 0.1–3.0 °C at Nakhchivan, Shahbuz, and Sharur (54–57%) and 3.1–6.0 °C at Ordubad and Julfa (46–48%), while Shahbuz showed higher recurrence in −3.0 to 0.0 °C; seven intervals were observed. In April, minima were 6.1–9.0 °C at most stations (63–68%), with Shahbuz dominated by 3.1–6.0 °C (57%), and higher minima (12.1–15.0 °C) were least frequent at Ordubad and Julfa (2–3%); five intervals overall. In May, minima were most frequent in 12.1–15.0 °C at Ordubad (75%) and Julfa (83%), and 9.1–12.0 °C at Nakhchivan (60%), Shahbuz (71%), and Sharur (87%), spanning two to three intervals depending on station (Figure 16).

In June, minimum temperatures spanned five gradation intervals, with Ordubad and Julfa showing four and other stations three. Dominant classes were 15.1–21.0 °C at Ordubad and Julfa, 12.1–18.0 °C at Nakhchivan, and 12.1–15.0 °C at Shahbuz and Sharur (Figure 17). In July, minima shifted higher, peaking at 18.1–24.0 °C at Ordubad and Julfa, 15.1–18.0 °C at Nakhchivan, and 15.1–18.0 °C at Shahbuz and Sharur. August distributions were similar to July.

In September, Tmin distributions varied among stations. Ordubad and Julfa peaked at 15.1–18.0 °C (57–63%), with secondary peaks at 18.1–21.0 °C; Nakhchivan was dominated by 12.1–15.0 °C (68%), while Shahbuz and Sharur peaked in mid-range classes (70–84%). In October, minima showed pronounced spatial variability: Ordubad and Nakhchivan peaked at 6.1–12.0 °C, Shahbuz at 6.1–9.0 °C (63%), Sharur at 6.1–9.0 °C (60%), and Julfa spanned 0.1–18.1 °C, with highest recurrence at 6.1–9.0 °C (48%). In November, minima were mainly negative or low positive, with notable spatial variability: −6.0 to −3.1 °C occurred once at Shahbuz, −3.0 to 0.0 °C at all stations (2–29%), 0.1–3.0 °C at 9–59%, 3.1–6.0 °C at 13–71%, and 6.1–9.0 °C at 0–11% (Figure 18).

The results of minimum temperature recurrence across all months and stations are presented in Figure 19. As shown, the temperatures were recorded across 16 gradation intervals, ranging from the lowest –21.0 to –18.1 °C to the highest 24.1–27.0 °C.

Analysis of Tmin distributions in Nakhchivan AR highlights strong altitudinal and orographic effects



September October November

Fig. 18. Repetition of average monthly minimum air temperatures in Nakhchivan AR during autumn months in different gradations

on extreme cold. The lowest class (−21.0 to −18.1 °C) occurred only at Nakhchivan (0.6%) and Sharur (0.3%), while the higher-elevation Shahbuz (~400 m above) showed none, indicating that elevation constrains extreme cold events and underscores topography's role in local climatic responses.

Spatial variations in Tmin classes (−18.0 to −15.1 °C at Julfa and Shahbuz vs −15.0 to −12.1 °C at Ordubad) underscore topographic and local microclimate influences. Non-monotonic, oscillatory patterns across stations indicate multiple thermal regimes and significant statistical heterogeneity in minimum temperature fields.

Station-specific Tmin patterns reveal distinct thermal characteristics. Ordubad spans −3.0 to 21.0 °C with relatively uniform recurrence (10.1–12.7%), Julfa peaks at low-moderate (−3.0 to 3.0 °C) and high (21.1–24.0 °C) classes, Nakhchivan is dominated by moderate temperatures (6.1–21.0 °C), Shahbuz exhibits a narrower range (−3.0 to 3.0 °C and 6.1–15.0 °C) reflecting thermal stability from elevation, and Sharur's 12.1–15.0 °C maxima indicate lower elevation and stronger continental influence.

Tmin distributions indicate that local microclimates modulate regional warming sensitivity. Station variability reflects differential responses to global and regional drivers. Absence of extreme cold at higher elevations and dominance of moderate-to-high classes suggest upward shifts in temperature extremes and reduced severe cold, emphasizing topography and local climate controls on heterogeneous climate change impacts in Nakhchivan.

Conclusion

This study provides a comprehensive assessment of the long-term dynamics of monthly mean maximum and minimum temperature anomalies in the Nakhchivan AR over the period 1961–2023, relative to the 1961–1990 baseline. The results clearly indicate a persistent and seasonally differentiated warming trend across the region.

A key finding is that warming is mainly driven by increases in maximum (daytime) temperatures, which show stronger and more consistent positive trends than minimum (nighttime) temperatures

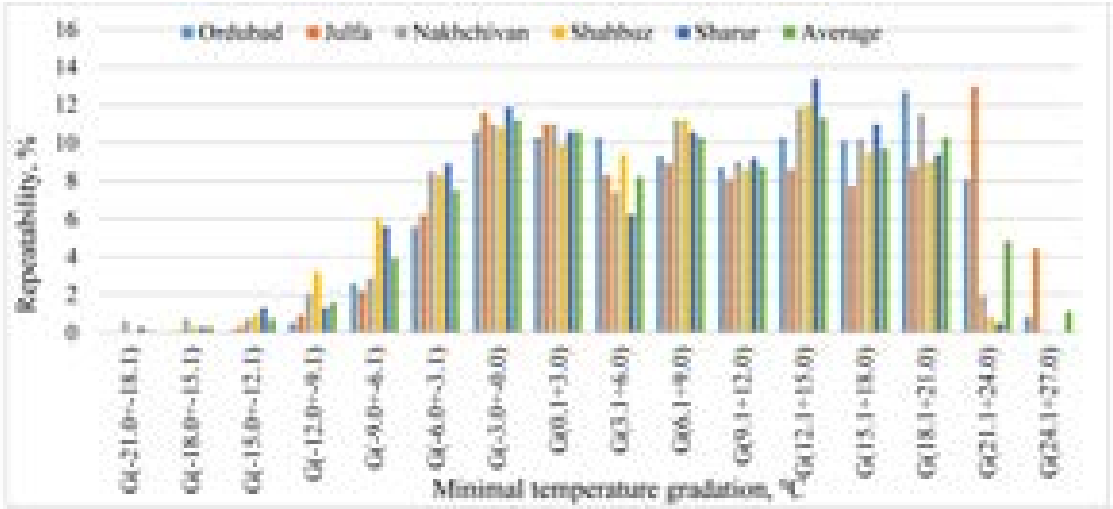


Fig. 19. Repetition of average monthly minimum air temperatures in the Nakhchivan AR in 1961-2023 years period in different gradations

in most months. This asymmetry indicates an intensification of the diurnal temperature range and emphasizes the dominant role of daytime heating in regional climate change.

Seasonal analysis shows that winter warming peaks in February, with significant increases in both temperature types, while other winter months are weaker and more variable. Spring warming occurs in all months, strongest in March, suggesting an earlier onset of warm conditions. Summer warming is significant for maximum temperatures, especially in June and August, whereas minimum temperatures show weaker trends. In autumn, warming is significant in September and October, decreasing toward November.

Another important feature is the clear temporal shift in anomaly patterns. Negative temperature anomalies dominated during the earlier period (1961–1992), whereas positive anomalies became markedly more frequent and intense during the later period (1993–2023). This shift provides strong evidence of an accelerated warming regime in recent decades.

The gradation-based analysis of maximum air temperature (1961–2023) reveals clear seasonal patterns and elevation-dependent spatial variability. Low temperatures dominate in winter, followed by rapid spring warming and dominant summer gradations (30–36 °C), with extremes up to 39–42 °C. In autumn, temperatures decline to intermediate ranges. The wide range (−9 to 42 °C) and 17 gradation intervals indicate high climatic diversity and higher temperature frequencies in lowlands.

Similarly, minimum temperature analysis shows strong seasonal and topographic influences. Low values prevail in winter, while higher Tmin classes dominate in summer. Tmin ranges from −21 to 27 °C (16 intervals). Spatial patterns indicate fewer extreme cold events at higher elevations and broader variability in lowlands, confirming reduced cold extremes and a heterogeneous, locally controlled warming pattern.

Overall, the findings demonstrate that the climate of the Nakhchivan AR has undergone significant warming over the past six decades, characterized by strong seasonal variability and a dominant contribution of increasing maximum temperatures.

The identified warming patterns – particularly the stronger rise in daytime temperatures and seasonal asymmetry – underscore the need for region-specific adaptation strategies. In the Nakhchivan AR, priorities include improved water management under higher evaporation, optimized agricultural practices, and strengthened heat-risk management. The dominance of maximum temperature increases also points to growing heat stress risks, relevant for public health and energy planning.

Future research should address extreme temperature indices (e.g., heatwaves and cold spells) and examine atmospheric circulation and land–atmosphere interactions driving these trends. The use of high-resolution climate models and scenario-based projections, along with sectoral impact assessments (agriculture, hydrology, health), would enhance climate risk evaluation and adaptation planning.

Конфлікт інтересів: автор повідомляють про відсутність конфлікту інтересів

Декларація про використання генеративного штучного інтелекту: автор підтверджує, що під час підготовки рукопису не використовувалися інструменти штучного інтелекту.

Conflict of Interest: The author declares no conflict of interest.

Declaration of use of generative artificial intelligence: The author confirm that no AI tools were used during the preparation of the manuscript.

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Спостережувані зміни щомісячних максимальних та мінімальних температур у Нахчиванській автономній республіці (Азербайджан) між 1961 та 2023 роками

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АНОТАЦІЯ

Дослідження спрямоване на розробку та вдосконалення методів дослідження для виявлення змін, викликаних кліматом, з особливим акцентом на максимальні та мінімальні температури повітря. Зокрема, воно спрямоване на створення надійних статистичних та спектральних методів, які можуть ідентифікувати часові тенденції, добові коливання та екстремальні температурні явища. Інтегруючи спостережувані температурні записи з оптимізованими аналітичними інструментами, дослідження має на меті підвищити точність і надійність регіональних кліматичних оцінок. Температурні аномалії були пов'язані з кліматологічною нормою ВМО 1961–1990 років, а швидкості потепління/похолодання (°C/десятиліття) кількісно визначали часові тенденції. Використання непараметричних методів, рухомих часових вікон та аналізу частоти повторюваності в різних градаціях температури дозволило надійно виявляти довгострокові зміни, нещодавні зрушення та асиметрії в

ІНФОРМАЦІЯ ПРО СТАТТЮ :

Рукопис надійшов
9 лютого 2026

Отримано після рецензування
29 квітня 2026

Затверджено до друку
25 травня 2026

Опубліковано онлайн
30 травня 2026

розподілі температури. За період 1961–2023 років було встановлено стабільне та широкомасштабне підвищення максимальної температури протягом усіх місяців і на всіх станціях. Найбільш інтенсивне потепління спостерігається взимку, зокрема у лютому (до 1,18°C/десятиліття), навесні – у березні (до 0,78°C/десятиліття), влітку – з червня по серпень (до 1,50–2,09°C/десятиліття) та восени – з вересня по жовтень. Найбільш статистично значущі тенденції Tmax характерні для весни (до 93% випадків) та літа (до 87%), що свідчить про найбільшу стабільність потепління протягом теплого сезону. Аналіз різних кліматичних періодів виявляє інтенсифікацію темпів потепління максимальної температури з часом, особливо після 1980-х років та найпомітніше протягом 1991–2023 років. Мінімальна температура демонструє більш складну та неоднорідну поведінку, включаючи стабільне потепління взимку, змішані тенденції навесні, локалізоване похолодання влітку (липень) та виражені просторові контрасти восени. Було встановлено, що клімат регіону характеризується зростанням екстремумів температур, зростанням частоти класів високих температур та посиленням міжсезонних та міжстанційних контрастів. Швидке підвищення максимальних температур навесні та влітку може негативно вплинути на різні сектори економіки в найближчі десятиліття. Такі дослідження є важливими для розуміння зміни клімату та відіграють вирішальну роль у моніторингу та аналізі кліматичних тенденцій для підтримки політиків у стратегіях пом'якшення наслідків та адаптації.

Ключові слова:

Нахчиванська автономна область Азербайджану, зміна клімату, аномалії максимальної та мінімальної температури, лінійний тренд, градація температури, різні кліматичні періоди, частота класів високих температур, асиметричне потепління максимальних та мінімальних температур/

https://doi.org/10.26565/2410-7360-2026-64-20

УДК 911.3:711.2:659.2

Географічні чинники територіального брендингу у стратегії місцевого розвитку (на прикладі Ковалівської сільської громади)

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АНОТАЦІЯ

Територіальний брендинг, якщо розглядати його через призму географічних чинників, передбачає концептуальне позиціонування певної території шляхом виокремлення її унікальних особливостей. Специфічні природні, культурні чи економічні характеристики місцевості при їх ефективному використанні надають різному колу зацікавлених осіб (бізнес-спільнота, місцеві жителі, потенційні інвестори) можливості для розвитку підприємницької діяльності, формуванню впізнавального іміджу території, а також підвищенню якості життя мешканців. Створення індивідуального профілю місцевості як одна із задач брендингу передбачає довгостроковий розвиток економіки території, через стимулювання галузей, що мають найбільший потенціал для зростання. Виходячи з цього, у межах даної публікації у якості об'єкту дослідження було обрано Ковалівську сільську громаду Київської області. На її прикладі було розглянуто модель територіального брендингу не лише як маркетингового інструменту, а як комплексного підходу, що дозволяє інтегрувати локальну економіку в систему функціонування регіонального ринку. Проведений аналіз Ковалівської ОТГ та підприємств, що функціонують на її території дозволив визначити, що основним напрямом економічної діяльності є сільське господарство. Майже вся земельна площа, що не зайнята лісовими масивами, активно використовується для аграрного сектору. Відсутність стратегічних документів, які б повноцінно описували економічний профіль громади, створює невизначеність щодо її формалізованої спеціалізації. Для усунення цієї прогалини було проведено оцінку географічних чинників, що впливають на формування територіального бренду, як одного з інструментів активізації місцевого розвитку. Результати дослідження виявили помітну диспропорцію у рівнях соціально-економічного розвитку в межах громади: окремі населені пункти, зокрема Ковалівка (адміністративний центр), Мар'янівка, Устимівка та Пологи демонструють значно вищий потенціал як для проживання населення, так і розвитку підприємництва, що вимагає диференційованого підходу до формування бренду території. Відповідно, зменшення внутрішньотериторіальної нерівності в межах ОТГ передбачає застосування підходу, який ґрунтується на суспільно-географічному аналізі механізмів територіального брендингу, зокрема у частині виявлення конкурентних переваг, структури ресурсного забезпечення та формування індивідуальних стратегій позиціонування окремих сільських населених пунктів з урахуванням їхнього потенціалу та потреб.

ІНФОРМАЦІЯ ПРО СТАТТЮ :

Рукопис надійшов
6 березня 2025

Отримано після рецензування
10 квітня 2026

Затверджено до друку
25 травня 2026

Опубліковано онлайн
30 травня 2026

Ключові слова:

територіальний брендинг, Ковалівська сільська громада, стратегія розвитку, географічні чинники, ідентичність, потенціал, ресурси, децентралізація.

Постановка проблеми

До закінчення реформи органів місцевого самоврядування (27.05.2020 р.) увага управлінського апарату новостворених територіальних громад була зосереджена переважно на адміністративній організації, розбудові інфраструктури та забезпеченні базових публічних послуг (у соціальній сфері), а не на довгостроковому стратегічному позиціонуванні чи розробці те-

Як цитувати : Уліганець Сергій, Крамаренко Олександр, Шинкаренко Уляна (2026). Географічні чинники територіального брендингу у стратегії місцевого розвитку (на прикладі Ковалівської сільської громади). *Вісник Харківського національного університету імені В.Н. Каразіна Серія «Геологія. Географія. Екологія»*, (64), 265–278. https://doi.org/10.26565/2410-7360-2026-64-20

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риторіального бренду. З початком повномасштабної війни в Україні відбулися глибокі трансформації у її регіональній економіці, демографічній структурі та забезпеченні діяльності інфраструктури, що зумовило необхідність переосмислення громадами своєї ідентичності та конкурентних переваг.

Забезпечення збалансованого розвитку територій нині потребує управлінських підходів і механізмів, здатних враховувати просторову організацію, економічний потенціал та соціокультурну ідентичність громад. У цьому контексті особливого значення набуває політика територіального брендингу як інструменту просторової диференціації та позиціонування громад. Попри те, що міські об'єднані територіальні громади (далі – ОТГ) зазвичай мають ширші інституційні та ресурсні можливості для впровадження політики територіального брендингу, саме сільські громади в умовах децентралізації стикаються з найбільшими викликами у формуванні конкурентного іміджу, зважаючи на обмеженість фінансових ресурсів, низьку щільність населення та залежність від первинного сектору економіки. З огляду на це, Ковалівську сільську громаду Київської області було обрано як модельний приклад для аналізу впливу географічних чинників на формування бренду території. Цей вибір зумовлений поєднанням низки факторів: наявністю вираженої просторової диференціації розвитку в межах громади, аграрною спеціалізацією, активною участю місцевої влади та бізнесу в промоції території та візуально-символічною репрезентацією сільського середовища як складової іміджу. На відміну від багатьох інших громад Київської області, які зазнали значних руйнувань під час військових дій, на обраній території не зафіксовано масштабних пошкоджень. Цей фактор вигідно позиціонує її в ландшафті післявоєнного відновлення, дозволяючи змістити фокус з відбудови на довгостроковий стратегічний розвиток.

Аналіз останніх досліджень і публікацій

Боротьба за інвестиції, споживачів, кваліфіковані кадри зумовили появу наукових робіт з дослідження брендингу територій, його систематизації та практичного застосування. У 1993 році книга Ф. Котлера, Д. Хайдера, І. Рейни «Маркетинг територій: залучення інвестицій, промисловості і туризму в міста, штати і країни» стала першою, що описала маркетингові процеси територіального розвитку, обґрунтувала актуальність формування позитивного іміджу та його важливість у розрізі конкурентної ринкової боротьби [21]. Наступною фундаментальною працею є робота Саймона Анхольта, який у 2002 році вперше використав термін «брендинг територій» та запропонував комплексний підхід до його розуміння [3]. На відміну від фокусних трактувань «брендингу територій», що здебільшого асоціювалися з туризмом та позитивним іміджем регіону, С. Анхольт розробив концепцію, що складається з шести елементів: туризм, експорт, люди, культура та надбання, інвестиції та імміграція, зовнішня і внутрішня політики. Його робота значно розширила традиційне сприйняття брендингу територій та стала фундаментом подальших наукових досліджень у цій сфері. Зокрема, К. Дінні, один з найбільших світових спеціалістів у сфері брендингу територій, відзначає цей процес як найбільш стратегічно важливий у формуванні конкурентоспроможності не лише міста чи регіону, а й держави [11]. У своїй книзі, Place Branding: Glocal, Virtual and Physical, Identities Constructed, Imagined and Experienced, Роберт Говерс акцентує увагу на фундаментальній ролі населення у створенні регіонального бренду [15]. Вітчизняна науковиця О. Кузьмук [22] визнала бренд території одним з головних чинників ефективного місцевого розвитку. В свою чергу, Т. Нагорняк наголошував, що брендинг територій – це не лише процес представлення та просування території, а й формування конкурентоздатної та ліквідної одиниці на світовому ринку [25].

Сучасні підходи до брендингу територій підкреслюють перехід від традиційного управління «зверху-вниз» до моделей, що передбачають інтеграцію різних факторів впливу, які допомагають меншим адміністративно-територіальним утворенням посилювати своє позиціонування на вищих організаційних рівнях. Проведені на сьогодні дослідження [1; 24; 35] показують, що серед зовнішніх факторів географічні чинники розвитку значною мірою обумовлюють характер територіальної організації та економічної діяльності (сфера виробництва, туризм, логістика, торгівля тощо) певної місцевості. Тема територіального брендингу знаходиться переважно в предметній області вивчення сфери маркетингу та економіки, зокрема науковцями [8; 23], які вивчають його комерційне та стратегічне застосування. Дослідники, які працюють у зазначеному напрямку, аналізують, як ідентичність території, сформована за допомогою брендингових ініціатив, впливає на сприйняття споживачами, формування ринкової поведінки та подальший місцевий економічний розвиток.

Перетин географії та брендингу можна розглядати як частину маркетингової стратегії, що пов'язує економічні результати з побудовою іміджу місця. Серед останніх досліджень

[5; 7] варто відмітити появу концепції «terroir washing», яка найчастіше зустрічається у французьких публікаціях, і означає практику, коли компанії експлуатують або перебільшують місцеві географічні та культурні особливості з комерційною та маркетинговою метою.

Для популяризації певного бренду профільні фахівці часто звертаються до геомаркетингу як концепції, яка поєднує географічні інформаційні системи (ГІС) з маркетинговими стратегіями для кращого розуміння та задоволення потреб споживачів на основі географічних даних [39]. Такий підхід передбачає використання просторових даних і даних про місцезнаходження для аналізу ринкових тенденцій, поведінки споживачів і ефективності бізнесу залежно від географічних факторів, таких як щільність населення, розподіл доходів, близькість до отримувача послуг або конкурентів.

Територіальний брендинг слугує засобом диференціації у конкурентному глобальному середовищі. Дослідження, яке підкреслює те, що в умовах глобальної конкуренції за ресурси, – людські, фінансові чи туристичні – брендинг територій стає критично важливою стратегією, представлене у роботі українських вчених [36]. Автори зазначають, що створення та просування територіальних брендів дозволяє містам і регіонам вирішувати соціально-економічні проблеми, завдяки «правильно» сформованому географічному образу (природні ресурси, історичні особливості, економіка подій, сучасні фестивалі та свята). У розрізі вивчення географічних чинників територіального розвитку цікавою є публікація [2], у якій авторка підкреслює, що територія – це не просто фізичний простір, а соціальний продукт, сформований завдяки поєднанню різної спрямованості факторів: ландшафтів, природних ресурсів, історико-культурної спадщини, і навіть особливостей локальної економіки, наприклад, виробництва товарів із захищеним географічним зазначенням.

Враховуючи прив'язаність дослідження до локального рівня, доцільно згрупувати наукові публікації за напрямами аналізу, що дозволяє краще охопити змістовне наповнення сучасної наукової дискусії з проблематики територіального брендингу. Першу групу складають роботи, у яких висвітлюються теоретико-методологічні засади територіального маркетингу, зокрема його адаптація до умов децентралізації, ролі територіального продукту, цільових аудиторій та маркетингового комплексу (4P+2P). У цьому напрямі працюють такі дослідники, як Г. Олексюк, Н. Попадинець та Н. Самотій [26]. Другу групу становлять дослідження, у яких акцент зроблено на соціокультурних аспектах брендингу громади, зокрема на формуванні локальної ідентичності, згуртованості населення та підвищенні привабливості території через залучення мешканців до стратегічного планування. У цьому контексті вагомий внесок зроблено О. Н. Євтушенком та М. М. Сусловим, які розглядають брендинг як інструмент формування колективної ідентичності та активізації участі громади в реалізації заходів розвитку [38]. Третій напрям охоплює праці, де місцеві громади розглядаються як повноцінні суб'єкти регулювання розвитку із визначеними класифікаційними ознаками, функціями й формами управлінської взаємодії, що безпосередньо впливає на ефективність брендингових стратегій. Тут слід відзначити роботу Л. Беновської [4], яка акцентує на інституційній спроможності громади як основі для формування цілісного бренду території.

Актуалізація проблем управління розвитком територій в умовах російсько-української війни зумовила появу низки нових досліджень, що фокусуються на просторових, економічних і соціальних трансформаціях в Україні. За масштабом дослідження виділено три рівні аналізу: національний, регіональний і локальний. На національному рівні [19;31;37] увага зосереджена на макроекономічній ситуації в умовах війни, наявних міжрегіональних диспропорціях та необхідності узгодження процесів відбудови згідно з Планом відновлення, розрахованим на 10 років (2023-2032). На регіональному рівні [6;16] вивчаються наслідки війни для українських секторів економіки, що підкреслює складність у їх відродженні навіть у регіонах, віддалених від бойових дій. На локальному рівні [13; 30] вивчаються територіальні громади (сільські, міські, селищні), де розглядається їх бюджетна стійкість, децентралізаційні практики, перспективи відбудови, проблеми сільського ринку праці тощо

Виділення невирішених раніше частин загальної проблеми. Нові можливості для розвитку територіальних громад, що були створені завдяки реформі місцевого самоврядування та територіальній організації влади за принципом децентралізації, суттєво підвищили значення територіального брендингу з огляду на формування позитивного іміджу, інвестиційної конкурентоспроможності та ефективності сталого розвитку громад. Зростання такої ролі, в свою чергу, вимагає особливої уваги до ландшафтно-культурних особливостей регіону, його просторових характеристик, ресурсної бази та локальних традицій.

Незважаючи на початок реформи багаторівневого самоврядування (так званої реформи децентралізації) в Україні, значна частина територіальних громад досі перебуває в процесі розроблення програмних документів соціально-економічного розвитку [33]. Відсутність чіт-

ко сформульованих стратегій, завдань і заходів розвитку ускладнює впровадження брендингу територій, який є ключовим інструментом підвищення їх конкурентоспроможності та інвестиційної привабливості. З огляду на нерівномірність соціально-економічного розвитку громад, концепції їх брендингу мають ґрунтуватися на об'єктивному аналізі внутрішнього потенціалу. У цьому контексті географічні чинники відіграють важливу роль у просторовій організації та позиціонуванні громад, оскільки саме вони формують базові передумови для розвитку локальних переваг. Зокрема, транспортна доступність визначає рівень інтеграції громади в регіональні та національні логістичні ланцюги постачання; наявність природних ресурсів створює основу для розвитку виробничої та туристичної спеціалізації; демографічна структура впливає на кадровий потенціал, споживчий ринок і соціальну динаміку.

Економічне підґрунтя, сформоване під впливом цих чинників, зумовило активізацію наукових досліджень у сфері територіального брендингу, насамперед у таких галузях як економіка, маркетинг, PR, соціологія, державне управління та туризм. За результатами аналізу, проведеного А. Ясніковскі, у 2023 році, серед наукових робіт з питань брендингу територій домінують дослідження соціально-економічного спрямування 31,6%, бізнесу, менеджменту і бухгалтерського обліку – 25,9%, економіки, економетрики та фінансів – 10,3%, тоді як природничі науки про довкілля охоплюють лише – 7,9% [17]. Така ситуація вказує на необхідності посилення міждисциплінарного підходу шляхом включення наукових досліджень з географії, які дозволять виявити просторово-територіальні особливості та визначити їх роль у формуванні бренду.

Метою статті є визначення впливу географічних чинників на формування територіального брендингу та його ролі у стратегічних документах базового рівня управління. На прикладі Ковалівської сільської громади проаналізовано, як обрані чинники впливають на формування локальної ідентичності, сприйняття території та її економічного потенціалу.

Виклад основного матеріалу дослідження. Сучасні процеси глобалізації та децентралізації значно посилили економічну конкуренцію не лише між окремими галузевими компаніями, а й між державами та внутрішніми територіальними одиницями.

Спільною рисою більшості досліджень територіального брендингу є визнання його ключових цілей:

- підвищення рівня конкурентоспроможності регіону та створення позитивного іміджу регіону;
- розвиток туризму та соціально-патріотичне об'єднання населення;
- залучення інвестицій покращення економічного добробуту населення та регіону.

Важливість формування тісного зв'язку між цілями територіального брендингу та стратегічними завданнями державної політики є особливо актуальною, в контексті реалізації Державної стратегії регіонального розвитку на 2021-2027 роки (далі – Стратегія) [34]. Цей документ розроблено відповідно до Цілей сталого розвитку України на період до 2030 року, які, зокрема, передбачають сприяння поступальному, всеохоплюючому та сталому економічному зростанню. Відповідно до Цілей, в рамках Стратегії зазначено, що стратегічною метою державної регіональної політики є, серед іншого, ефективне використання внутрішнього потенціалу територій та підвищення конкурентоспроможності регіонів. Серед пріоритетів регіонального розвитку на період до 2027 року є розвиток людського капіталу, відновлення підприємницької діяльності та зростання економіки на основі внутрішнього потенціалу територій та регіональних смарт-спеціалізацій, сприяння економічному розвитку регіонів шляхом залучення інвестицій для реалізації інноваційних проектів.

Ефективне застосування брендингу територій з метою виконання поставлених завдань Стратегії потребує побудови чітких зв'язків між географічними чинниками територіального брендингу та відповідними цілями та завданнями. Для цього проведемо аналіз Стратегії з точки зору ключових цілей використання територіального брендингу, визначимо перелік завдань по їх досягненню та структуруємо основні географічні чинники (табл.1;2).

Представлена класифікація географічних чинників сформована з урахуванням структури ресурсного потенціалу території та теоретичних підходів суспільної географії до аналізу соціально-економічних процесів у територіальних системах. Такий підхід дає змогу систематизувати природні, господарські та соціокультурні передумови формування конкурентних переваг і розглядати їх як основу формування територіального бренду.

Перехід від загальнодержавної стратегії на інші рівні територіального управління: регіональний (Стратегія розвитку Київської області на 2021-2027 роки) та локальний (Стратегія розвитку Ковалівської громади, яка станом на 2025 рік відсутня) – вимагає адаптації визначених у межах даного дослідження цілей і географічних чинників (табл.1,2) до специфіки функціонування територій базового рівня [18]. З огляду на те, що територіальні громади в Україні отримали значні повноваження в ре-

Таблиця1 / Table 1

Взаємозв'язок територіального брендингу та стратегічного планування (створено авторами на основі [34])
Interconnection of territorial branding and strategic planning (compiled by the authors based on [34])

Цілі застосування територіального брендингу	Завдання Стратегії
підвищення рівня конкурентоспроможності регіону та створення позитивного іміджу регіону	Сприяння діяльності виробників крафтової та локальної продукції. Сприяння розвитку регіональних систем інноваційної інфраструктури (наукові парки та технопарки, хаби цифрових інновацій тощо). Забезпечення оновлення напрямів смарт-спеціалізації регіонів. Розроблення та впровадження механізмів підтримки проектів регіонального розвитку, спрямованих на розвиток пріоритетних видів економічної діяльності, визначених на засадах смарт-спеціалізації та необхідності переходу до кліматично нейтральної економіки.
розвиток туризму та соціально-патріотичне об'єднання населення	Створення умов для розвитку рекреаційно-туристичного потенціалу територій з урахуванням наявності природних та безпекових обмежень. Забезпечення розроблення регіональних та місцевих програм розвитку та використання рекреаційно-туристичного потенціалу територій. Сприяння формуванню локальних туристичних брендів та популяризації туристичного потенціалу регіонів і територіальних громад, зокрема з використанням цифрових технологій.
залучення інвестицій та покращення економічного добробуту населення та регіону	Стимулювання економічного відновлення в регіонах на принципах подвійного переходу ("зелений" перехід і цифрові трансформації). Підвищення інвестиційної привабливості територій, підтримка залучення інвестицій, популяризація інвестиційних можливостей регіонів. Сприяння залученню коштів міжнародної технічної допомоги та міжнародних фінансових організацій для реалізації публічних інвестиційних проектів для відновлення та розвитку територіальних громад. Сприяння залученню коштів міжнародної технічної допомоги та міжнародних організацій з метою забезпечення охорони культурної спадщини.

Таблиця 2 / Table 2

Основні географічні чинники, їх складові та фактори, що впливають на формування бренду територій (створено авторами на основі узагальнених наукових підходів [3], [12], [21], [40])
Key Geographical Factors, Their Components, and Influencing Factors on the Formation of Territorial Brands (compiled by the authors based on synthesized scientific approaches [3], [12], [21], [40])

Географічні чинники	Складові чинників	Основні фактори
Фізико-географічні	Територіально-природничі	Особливості рельєфу, біорізноманіття, клімату
	Екологічні	Стан екологічної безпеки регіону
Економіко-географічні	Технологічні	Галузево-наукова структура регіону
	Економічні	Відомі успішні компанії регіону, загальний рівень економічного розвитку регіону
	Інфраструктурні	Рівень розвитку логістично-виробничої інфраструктури, доступність та рівень трудових ресурсів
Суспільно – географічні	Соціально-демографічні	Рівень освіти населення, його економічний та соціальний добробут, структура населення регіону, рівень урбанізації, міграційна динаміка
	Історико-культурні	Рівень мистецько-освітнього розвитку регіону, наявність історичних об'єктів
	Політичні	Рівень відкритості та толерантності населення, органів самоврядування, державних структур, безпековий стан регіону
	Релігійні	Релігійний склад населення, наявність релігійних пам'яток
Туристично-рекреаційні	Туристичні	Розвинутість туристичної інфраструктури
	Рекреаційні	Наявність природних та штучних рекреаційних ресурсів

зультаті децентралізації, особливої уваги набуває актуалізація інформації на місцевому рівні щодо потенціалу ресурсів, які перебувають у розпорядженні громади. Для сільських громад одним із головних ресурсів на разі є земельні угіддя. Саме тому необхідність проведення дослідження в розрізі сільської громади зумовлена тим, що території, які зазнають постійного ресурсного освоєння, часто характеризуються несприятливими умовами щодо ключових чинників конкурентоспроможності. Низький рівень господарської організації, відсутність інфраструктури, недостатня кількість підприємств і, як наслідок, низький рівень конкуренції впливає на уповільнений розвиток економіки та соціальної сфери.

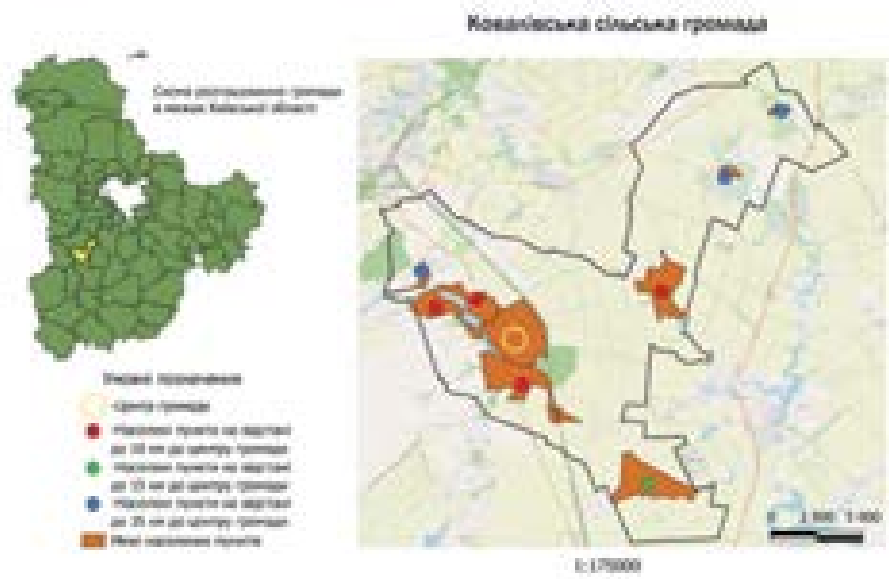


Рис. 1. Географічне положення та склад Ковалівської сільської громади (створено авторами в програмному середовищі QGIS на основі даних OpenStreetMap [29])
Fig. 1. Geographical location and composition of the Kovalivska rural community (compiled by the authors in the QGIS software environment based on OpenStreetMap data [29])

Ковалівська сільська громада була утворена 12 червня 2020 року в межах Білоцерківського району Київської області разом з 9 сусідніми селами: Вінницькі Стави, Кищинці, Ковалівка (центр ОТГ), Мар'янівка, Паляничинці, Пологи, Пшеничне, Устимівка, Червоне (рис.1) [28]. Чисельність постійного населення громади складає 9036 осіб, з них у с. Ковалівка проживає 1 600 осіб, у с. Червоне 858 жителів, у с. Паляничинці 652, у с. Устимівка 1869, у с. Пшеничне 630, у с. Пологи 1331, у с. Мар'янівка 1017, у с. Вінницькі Стави 657, у с. Кищинці 336 (рис.2). Загальна площа громади становить 231,60 км^2.

Головні сильні сторони громади проявляються у чотирьох умовних площинах: економічна стійкість, культурна спадщина, спортивна інфраструктура та загальна якість життя. Основою економіки громади, а отже її спеціалізацією є розвинений аграрний сектор, представлений насамперед агрофірмою «Світанок». Підприємство, засноване у 1993 році (колишня назва – «Колгосп імені Щорса»), нині входить до числа найбільших землевласників в Україні (на початок 2025 року земельний банк складає 80 тис. га) [27]. Диверсифікована аграрна діяльність, яка включає вирощування сільськогосподарських культур, переробку м'яса та виробництво продуктів харчування, забезпечує стійку економічну основу для громади. Функціонування потужного сільськогосподарського підприємства не лише створює можливості для працевлаштування місцевих жителів (≈ 700 осіб), а й сприяє покращенню інфраструктури та реалізації соціальних ініціатив. Економічна стабільність, зумовлена діяльністю такого підприємства, є критично важливим фактором сталого розвитку сільських територій.

Варто відзначити, що громада володіє значною культурною спадщиною, зокрема, завдяки своїм відомим історичним постатям. Так, у с. Мар'янівка, на батьківщині відомого оперного співака Івана Козловського (роки життя 1900-1993 рр.), була створена музична школа, що підкреслює культурну ідентичність села; тут також збереглася батьківська хата митця. Збереження історичних пам'яток та підтримка закладів культури сприяють зміцненню місцевих традицій, розвитку туристичного потенціалу та утвердженню локальної ідентичності. До важливих складових соціальної інфраструктури громади належать об'єкти, що створюють умови для розвитку спортивної та рекреаційної діяльності, яка фінансується переважно за рахунок інвестиційної підтримки.

Стадіон «Колос» (відкрито 19.10.2014) у с. Ковалівка є прикладом модернізованого спортивного об'єкту у сільській місцевості [14]. Після масштабної реконструкції (І етап –2014; ІІ– етап-2020) споруда вміщує понад 5000 глядачів і приймає професійні футбольні матчі, зокрема, для ФК «Колос Ковалівка», який виступає в українській Прем'єр-Лізі. Додатковим сучасним об'єктом спортивної інфраструктури є льодова арена «Світанок» (с. Ковалівка). Обладнана роздягальнями, вбиральнями, медичним пунктом та кафетерієм, арена підтримує різні види спорту на льоду, включаючи хокей та фігурне катання, а також масові сеанси катання на ковзанах. Арена є місцем тренування хокейної команди «Ковалівські Кабани», яка бере участь у чемпіонаті України з хокею з шайбою серед команд віком до 15 років. Наявність таких об'єктів не лише сприяє залученню місцевих жителів до занять спортом, але й по-

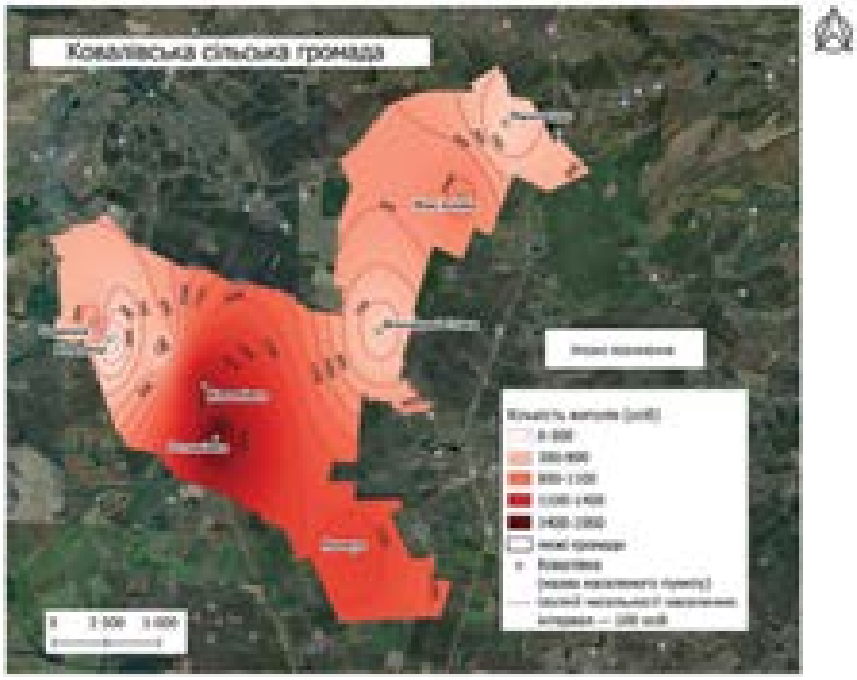


Рис. 2. Чисельність сільського населення в межах громади (кількість осіб) (створено авторами в програмному середовищі QGIS на основі даних порталу «Децентралізація» [10])
Fig. 2. Number of rural population within the community (number of people) (compiled by the authors in the QGIS software environment based on data from the "Decentralization" portal [10])

зиціонує громаду як потенційний регіональний центр спортивного розвитку Київщини.

Попри загальну наявність базових елементів інфраструктури в межах Ковалівської сільської громади, рівень її розвитку суттєво відрізняється між окремими населеними пунктами. Найкраще забезпеченим є адміністративний центр с. Ковалівка, що вирізняється якісним покриттям доріг, чистими громадськими місцями та доступністю до основних соціальних послуг, включаючи охорону здоров'я, освіту та державні установи. Вагому роль у підтримці цієї інфраструктури відіграє керівництво Агрофірми «Світанок». Водночас інші вісім сіл громади демонструють нижчий рівень розвитку, що зумовлює просторову нерівномірність та підкреслює необхідність системного планування територіального розвитку.

Незважаючи на високий рівень громадської активності мешканців Ковалівської громади у місцевому розвитку, комплексна оцінка географічних чинників, що впливають на брендинг території, ускладнюється відсутністю документів стратегічного планування. Наразі громада не має офіційних документів свого коротко (до 3 років), середньо (до 5 років) та довгострокового (до 7 років) розвитку, а саме стратегії, плану заходів з її реалізації, плану (програми) соціально-економічного розвитку, місцевих програм, плану відновлення та розвитку території тощо. Як вказано на офіційному сайті громади, наразі формується робоча група для створення комплексного плану розвитку, відповідно до нових правил, які набули чинності в Україні з 1 січня 2025 року [32]. В умовах такого інерційного сценарію розвитку, дії органів місцевого самоврядування призводять до стримування зростання місцевої економіки, створюючи потенційну напругу між представниками громадськості та підприємцями. Досягнення цілей повноцінного використання потенціалу території передбачає системну роботу у залученні всіх суб'єктів, здатних надавати спеціалізовані послуги.

Враховуючи відсутність чіткого бачення розвитку з боку місцевого керівництва, існує потреба у проведенні дослідження для визначення пріоритетних напрямків зростання та ефективного формування стратегічних меседжів розвитку. Для цього необхідно проаналізувати поточну структуру землекористування громади, оскільки вона дає уявлення про наявні ресурси, виклики та можливості на майбутнє. Існуючий розподіл земель є відправною точкою для розуміння природно-ресурсної бази і того, як її можна оптимально використати для розвитку (рис.3). Структура землекористування Ковалівської ОТГ свідчить про можливість диверсифікації функціонального використання територій, включаючи виробничу, рекреаційну та сервісну діяльність. Оскільки значна частина земель зайнята під сільське господарство, громада може зосередитися на створенні нішевого ринку для органічного або спеціалізованого сільського господарства, яке надає можливості для створення продуктів з доданою вартістю, таких як місцеві продукти, ремесла або



Рис. 3. Типи землекористування в межах громади (створено авторами в програмному середовищі QGIS на основі даних європейської системи «Copernicus» [9])
Fig. 3. Types of land use within the community (compiled by the authors in the QGIS software environment based on data from the European "Copernicus" system [9])

агропродовольчі фестивалі. Аналогічно, природні території дають можливість спрямувати діяльність в екотуризм. Інтеграція збереження довкілля з туризмом може не лише стимулювати місцеву економіку, але й покращити територіальний брендинг громади як екологічно свідомої, природоорієнтованої дестинації.

Робота над концепцією територіального бренду на основі географічних чинників передбачає визначення потенційних точок зростання для інвесторів та підприємців, які виявлять бажання встановити партнерство з місцевим бізнесом. З огляду на це, аналіз галузевої спеціалізації громади та стану її інфраструктури дозволяє окреслити напрями з найбільшим потенціалом для сталого розвитку та впровадження інновацій (табл.3) [20]. Усі зібрані дані лягають в основу структурованого плану територіального розвитку, спрямованого на оптимізацію використання простору та передбачення соціально-економічних навантажень. З приводу останнього можна зауважити, що Ковалівська громада має переважно аграрну структуру економіки, що позиціонує її як провідного гравця у сільськогосподарському виробництві Київської області, а також зумовлює те, що більшість населення є самозайнятою у цій сфері. Комерційна інфраструктура в селах громади включає продовольчі магазини та місцеві ринки, що загалом полегшує доступ до основних товарів. Однак відсутність великих промислових підприємств свідчить про потенційну прогалину в диверсифікації місцевої економіки. На разі, Ковалівська ОТГ асоціюється з мирним місцем для проживання, із відносно задовільним станом навколишнього середовища, де якість життя відповідає спокійному ритму трудової зайнятості. Аналіз відкритих джерел дозволяє визначити орієнтовну структуру місцевої економіки, в якій домінує сільське господарство (70%) та представлена торгівля (30%). Можливості для використання земельних ресурсів громади у цілях розвитку промисловості, туризму чи сталого сільського господарства безперечно залежать від умов соціально-економічного розвитку, обсягу інвестицій, спрямованих на створення необхідної інфраструктури, а також від мотивації для залучення бізнесу та місцевого населення. Поточний потенціал громади не використовуються повною мірою, адже сукупність тих об'єктів історико-культурного значення чи місцевої спортивної інфраструктури потребує створення цільових програм щодо ефективного функціонування. У Стратегії розвитку Київської області на 2021-2027 роки прописані такі завдання:

– 2.3.4.2.розробка та проведення інформаційної кампанії з просування товарів та послуг,

ISSN 2410-7360 (Print)
ISSN 2411-3913 (Online)
Вісник Харківського національного університету імені В.Н. Каразіна Серія «Геологія. Географія. Екологія» 2026 64 С. 265–278
Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology 2026 64 265–278

Таблиця 3 / Table 3

Матриця оцінки інфраструктурних об'єктів сіл (створено авторами на основі офіційних веб-ресурсів щодо інфраструктури населених пунктів [18], [20], [27], [28])

Matrix for assessing infrastructure facilities in villages (compiled by the authors based on official web resources regarding settlement infrastructure [18], [20], [27], [28])

Назва населеного пункту	Сільське господарство	Торгівля	Промисловість	Транспорт	Медичні установи	Освіта	Релігійні установи	Інші об'єкти
Ковалівка (адміністративний центр)	Розвинене (агрофірми): ФГ «Дубовий Бір-1;2;3), ТОВ «Гюрза», ПСП «Агрофірма «Світанок»	Продуктові магазини, ринок	Немає великих промислових підприємств	Автобусні маршрути, якісне дорожнє покриття; до м. Біла Церква –24,2 км, до м. Київ –72,9 км	Амбулаторія загальної практики (спеціалізоване лікування у м. Біла Церква)	Академічний ліцей	Церква Різдва Пресвятої Богородиці	Футбольний клуб, ландшафтний парк, будинок культури, відділення Нової Пошти, АТ «КІБ», дитячий садок, готель, дитяче кафе, суше-бар, ресторан піцерія, салон краси, оздоровчо-профілактичний комплекс
Мар'янівка	Розвинене (вирощування зернових, овочів та фруктів): ТОВ «МК-АГРО», ФГ «ЗІЛ», ТОВ «ГАРАНТ-1»	Продуктові магазини, ринок	Немає великих промислових підприємств	Розвинена транспортна інфраструктура; до м. Біла Церква –34,6 км, до м. Київ –62,3 км	Фельдшерсько-акушерський пункт	Гімназія	Релігійна організація «Релігійна громада парафія покрови Пресвятої Богородиці»	Музична школа, музей-садиба, відділення Нової Пошти, дитячий садок, кафе
Пологи	Вирощування зернових, а також тваринництво: СТОВ «ПОЛОГІВСЬКЕ», ФГ «Тетяна-1», ФГ «ОБРІЙ», ФГ «МАРК», СФГ «САТУРН»	Торговельні заклади: магазини з товарами повсякденного вжитку	Відсутні промислові підприємства	Зручне транспортне сполучення: до м. Біла Церква – 18,6 км, до м. Київ-80,4	Фельдшерсько-акушерський пункт	Ліцей	Успінська церква	Будинок культури, відділення ощадбанку, Укрпошти, Нової пошти, дитячий садок
Вінницькі стави	Розташована центральна садиба колгоспу ім. Кірова	Продуктовий магазин	Відсутні промислові підприємства	Знаходиться біля автостради Київ-Одеса, до м. Біла церква –27,8 км, до м. Київ-69,7 км	Відсутні	Гімназія	Церква Пресвятої Богородиці	Бібліотека, клуб, дитячий садок, Укрпошта
Паляничинці	СФГ «Нива» та ін. (13)	Продуктовий магазин	Відсутні промислові підприємства	Знаходиться на автотрасі Фастів —Біла Церква (27 км). Біля села розташований пасажирський залізничний зупинний пункт Козятинської дирекції Південно-Західної залізниці. Відстань до м.Київ-70 км	Відсутні	Відсутні	Церква св. Михаїла, Казанської Богоматері,	Відділення Нової Пошти, клуб, готель

Продовження Таблиці 3 / Continuation Table 3

Пшеничне	Агростанція НАУ	Продуктовий магазин	Відсутні промислові підприємства	До м. Біла Церква – 36,1 км, до м. Київ – 65,1	Відсутні	Гімназія	Релігійна громада парафія «На честь ікони Божої матері»	Відділення Нової Пошти, Укрпошти
Устимівка	ТОВ «АГРО-СІД» та ін. (10)	Мінімаркет	Відсутні промислові підприємства	До м. Біла Церква – 22,2 км, до м. Київ –76 км. Село є проміжною станцією Південно-Західної залізниці	Амбулаторія	Ліцей	Церква Святого Пантелеймона ПЦУ	Відділення Нової Пошти, Укрпошти, кафе
Червоне	ПАТ «ПТАХІВНИК», ТОВ ФІРМА «КВАДРАТ»	Продуктовий магазин	Відсутні промислові підприємства	До м. Біла Церква – 32,2 км, до м. Київ –74,2 км.	Фельдшерсько-акушерський пункт	Початкова школа	Відсутня	Відділення Нової Пошти, Укрпошти, будинок культури
Кищинці	ПСП «ХВИЛЯ КАМ'ЯНКИ», АТ «ГОСПОДАР»	Продуктовий магазин	Відсутні промислові підприємства	До м. Біла Церква- 29,7 км, до м. Київ –72,7 км	Відсутня	Відсутня	Храм	Відділення Нової Пошти

вироблених підприємствами Київської області, у тому числі через відповідне регіональне брендування продукції «Вироблено на Київщині»;

– 3.1.4.3.просування результатів досліджень і розробок та інноваційної продукції на міжнародні ринки, в т.ч. формування бренду «Київщина інноваційна».

Відповідно, комплекс заходів, які необхідно реалізувати в регіональних стратегічних документах має відображатися і на базовому рівні. Розроблення та впровадження механізмів, що стимулюватимуть активність у межах ОТГ, підвищить якість проєктних пропозицій та дозволить залучити нові інвестиції для розвитку.

Висновки

Результати проведеного дослідження підтверджують важливість врахування географічних чинників у формуванні територіального бренду як інструменту стратегічного розвитку сільських громад в умовах децентралізації. На прикладі Ковалівської сільської громади встановлено, що просторові, соціо-демографічні, економіко-географічні та культурні особливості відіграють вагому роль у формуванні локальної ідентичності, сприйняття громади зовнішніми стейкхолдерами та зміцненні її економічного потенціалу.

Виявлена просторово-соціальна диференціація в межах громади зумовлює необхідність впровадження диференційованих підходів до брендингу для кожного населеного пункту з урахуванням їх ресурсного потенціалу, спеціалізації та суспільних потреб. Виявлено, що відсутність офіційно затверджених стратегічних документів на місцевому рівні перешкоджає формуванню цілісного бренду та обмежує можливості координації економічного розвитку, залучення інвестицій, а також просування унікальних переваг громади на регіональному та національному рівнях.

Практичне значення дослідження полягає в розробці методичного підходу до аналізу географічних чинників брендингу, який може бути інтегрований у стратегії місцевого розвитку територіальних громад. Запропонована класифікація чинників (фізико-географічні, економіко-географічні, суспільно-географічні, туристично-рекреаційні) дозволяє сформувати основу для створення комплексної бренд-стратегії, що відповідатиме ресурсному потенціалу та соціо-економічному профілю Ковалівської громади.

У подальших наукових розвідках доцільно зосередитися на розробленні системи індикаторів ефективності територіального бренду, оцінці його впливу на обсяги інвестицій, рівень соціальної згуртованості та економічної самодостатності громад у післявоєнний період.

Внесок авторів: всі автори зробили рівний внесок у цю роботу
Конфлікт інтересів: автори повідомляють про відсутність конфлікту інтересів
Декларація про використання генеративного штучного інтелекту: автори підтверджують, що під час підготовки рукопису не використовувалися інструменти штучного інтелекту.

Authors Contribution: All authors have contributed equally to this work
Conflict of Interest: The authors declare no conflict of interest

Declaration of use of generative artificial intelligence: The authors confirm that no AI tools were used during the preparation of the manuscript.

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Geographical factors of territorial branding in local development strategy (on the example of Kovalivska rural community)

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ABSTRACT

Territorial branding, when viewed through the prism of geographical factors, involves the conceptual positioning of a certain territory by highlighting its unique features. Specific natural, cultural, or economic characteristics of the area, if used effectively, provide various stakeholders (business community, local residents, potential investors) with opportunities for business development, formation of a recognizable image of the territory, and improvement of the quality of life of residents. The **purpose of the study** was to determine the impact of socio-geographical factors on the formation of territorial branding and its role in strategic documents of the basic level of management. Creating an individual profile of a locality as one of the branding tasks involves the long-term development of the territory's economy by stimulating industries with the greatest potential for growth. Based on this, the Kovalivska rural community of the Kyiv region was chosen as the object of research in this publication. Given that the concept of territorial branding should be consistent with individual strategic documents, the **research methodology** was based on the characterization of the system of documents at different organizational levels: State Strategy for Regional Development for 2021-2027, Kyiv Region Development Strategy for 2021-2027. In order to analyze the local economic structure, data were taken from the official website of the community, as well as the Decentralization website and the Open Data Bot service. QGIS was used to process geodata on the spatial distribution of the population and the structure of land use distribution.

Results. The analysis of the Kovalivska UTC and the enterprises operating on its territory allowed us to determine that the main economic activity is agriculture. Almost all of the land area not occupied by forests is actively used for the agricultural sector. The lack

ARTICLE INFO

Manuscript received
6 March 2025

Revised manuscript received
10 April 2026

Manuscript accepted
25 May 2026

Available online
30 May 2026

of strategic documents that fully describe the economic profile of a community creates uncertainty about its formalized specialization. To address this gap, an assessment was made of the geographical factors that influence the formation of a territorial brand that can stimulate development. The results of the study revealed a noticeable disproportion in the levels of socio-economic development within the community: certain settlements, including Kovalivka (the administrative center), Marianivka, Ustymivka, and Polohy, demonstrate a much higher potential for both residential and business development, which requires a differentiated approach to building the territory's brand.

The **scientific novelty** lies primarily in the fact that the positioning of any territory involves the use of previously developed materials that create conditions for the systematic implementation of measures to increase the competitiveness of the community in both local and regional markets. Geographical factors were selected taking into account the fact that they determine the competitive advantages of a particular territory and provide opportunities for achieving high efficiency in the relevant area. The **practical significance** of the results obtained is primarily determined by the effectiveness for local authorities involved in the development of strategic documents. In these conditions, the task of the relevant developments that have been made is to maintain competitive advantages in the areas of specialization of the territory.

Keywords:

territorial branding, Kovalivska rural community, development strategy, geographical factors, identity, potential, resources, decentralization.

In cites: Uliganets Serhii, Kramarenko Oleksandr, Shynkarenko Ulyana (2026). Geographical factors of territorial branding in local development strategy (on the example of Kovalivska rural community). *Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology*, (64), 265–278. https://doi.org/10.26565/2410-7360-2026-64-20 [In Ukrainian]

https://doi.org/10.26565/2410-7360-2026-64-21

УДК 556.555(477.82)

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АНОТАЦІЯ

Світязь – найбільше й найглибше із Шацьких озер, рівень якого визначають опади, випаровування, підземне живлення та антропогенний вплив. Найбільш суттєві зниження рівня озера характерні у 2019-20 роках. Це ускладнює прогнозування й вимагає науково обґрунтованого управління. Метою статті є наукове обґрунтування особливостей формування, виділення сучасних тенденцій та чинників зміни рівневого режиму озера Світязь на основі аналізу гідрометеорологічних параметрів, елементів водного балансу озера та просторово-часових закономірностей їх коливань. Об'єктом дослідження є рівневий режим озера Світязь як результат дії природних та антропогенних чинників. Предметом дослідження є просторово-часові особливості коливань рівня води, природні й антропогенні чинники, що визначають водний баланс і рівневий режим озера Світязь. У дослідженні використано середньомісячні рівні води озера Світязь, середньомісячну температуру та кількість опадів за 1970–2024 рр., а також числа Вольфа як показник сонячної активності. Багаторічні та сезонні зміни рівня води проаналізовано за допомогою графіків і статистичних розрахунків. Визначено основні параметри сезонного циклу. Методом кореляційного аналізу проведено оцінку зв'язку рівня води з температурою, опадами та сонячною активністю. Визначено роки з мінімальними та максимальними рівнями води, проведено порівняння рівнів із метеорологічними умовами та циклом сонячної активності. Проаналізовано вплив головних чинників зміни рівневого режиму озера в умовах коливань клімату. Встановлено, що найбільшою мірою рівень води в озері залежить від метеорологічних умов Річна сезонність є домінуючим чинником формування рівневого режиму. На фоні річних циклів простежуються багаторічні хвилі з періодом 9,26 років. Встановлено кількісні закономірності впливу метеорологічних чинників та сонячної активності на багаторічну динаміку рівнів води озера Світязь. Розраховані параметри автокореляційної функції рівнів води та коефіцієнти кореляції між рівнями води, опадами та температурою повітря, визначена їх статистична значущість. Побудована періодограма часового ряду середньомісячних рівнів води. Проведена декомпозиція часового ряду рівнів води озера. Отримані результати можуть бути використані для розробки програм сталого управління лімносистемами Шацьких озер, природоохоронних заходів, моніторингу та адаптації до зміни клімату.

ІНФОРМАЦІЯ ПРО СТАТТЮ :

Рукопис надійшов
17 грудня 2025

Отримано після рецензування
6 травня 2026

Затверджено до друку
25 травня 2026

Опубліковано онлайн
30 травня 2026

Ключові слова:

озеро; рівні води озера; коливання рівнів; рівневий режим озера; чинники, що впливають на рівні води озера; живлення озера; підземний стік як джерело живлення; водний баланс озера; зміна клімату.

Вступ

Світязь – найбільше та найглибше із Шацьких озер. Його рівневий режим формується під впливом складної взаємодії атмосферних опадів, випаровування, підземного живлення, водообміну з сусідніми водоймами, дії антропогенних чинників. Протягом останніх кількох десятиліть озеру властиві суттєві міжрічні коливання рівнів води, що спричиняють гідроекологічні ризики, впливають на структуру прибережних екосистем, режим зволоження та розвиток рекреації. Особливо критичним у цьому відношенні був 2019 р. Кліматичні зміни, зокрема, збільшення температури повітря, зміна режиму випадання опадів і водного балансу,

Як цитувати : Фесюк Василь, Мороз Ірина (2026). Географічні чинники територіального брендингу у стратегії місцевого розвитку (на прикладі Ковалівської сільської громади). *Вісник Харківського національного університету імені В.Н. Каразіна Серія «Геологія. Географія. Екологія»*, (64), 279–292. https://doi.org/10.26565/2410-7360-2026-64-21

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визначають особливу актуальність наукового обґрунтування причин і механізмів зміни рівня води, прогнозування цих змін та реагування на прогнози. Недостатність довгострокових інструментально визначених гідрометеорологічних даних, фрагментарність гідрологічних та гідрогеологічних спостережень, не повне розуміння ролі підземного стоку у живленні озера та впливу меліоративних систем на водний баланс озера ускладнюють прогнозування майбутнього стану гідроекосистеми. В той же час розробка науково обґрунтованої оцінки рівневого режиму є необхідною умовою для сталого управління лімносистемами Шацьких озер, природоохоронних заходів, моніторингу та адаптації до наслідків зміни клімату.

Аналіз останніх досліджень і публікацій

Серед наукових робіт, присвячених дослідженню рівневого режиму озера Світязь, насамперед слід відзначити серію праць українських авторів, безпосередньо присвячених самому озеру. Батиметричні дослідження [1] уточнюють просторову структуру донного рельєфу та локалізацію підземних джерел живлення озера, що є дуже важливим для розуміння механізмів коливань рівнів. Робота [2] присвячена аномальним змінам рівня води в озері у 2019 р., демонструє реакцію Світязя на поєднання локальних гідрометеорологічних та басейнових чинників. У контексті геолого-геоморфологічних умов, які впливають на живлення озера, цікавими є дослідження реліктового карсту Світязя [3], вони пояснюють глибинні причини водночас стабільності та уразливості його рівневого режиму. Важливою віхою в комплексному дослідженні озера була монографія за ред. проф. Я.О. Мольчака про сучасний природно-господарський стан озера [4]. Дослідження тенденцій коливань річних та сезонних сум опадів на метеостанції Світязь [5] є підґрунтям для аналізу кліматично зумовлених трендів рівневих коливань. В роботі про меліорацію та ренатуралізацію ґрунтів Шацького регіону [6] обґрунтовано участь педосфери у місцевих та регіональних процесах водообміну. Оцінка вразливості поверхневих вод до кліматичних змін у роботі [7] інтегрує досліджуваний регіон у ширший простір кліматичних ризиків. Праці з екологічної оцінки води [8] та дослідження евтрофікації Шацьких озер [9] показують, що ці процеси безпосередньо залежать від рівневого режиму через зміни водного балансу й біогеохімічних циклів. Гідрологічна характеристика водних об'єктів Шацького НПП у роботі [10] є підґрунтям для розуміння тенденцій зміни рівня води у довгостроковій перспективі.

Також важливими для нашої роботи є праці переважно українських авторів, які розширюють регіональний контекст дослідження Світязя. Наприклад, стаття про особливості регіонального клімату та розподіл опадів на українсько-польсько-білоруському прикордонні [20] поглиблює розуміння гідрометеорологічних умов, що визначають живлення озера, роботи про вплив кліматичних змін на обміління Світязя [19] та зміни природних вод Шацького Поозер'я в контексті змін клімату [11] є важливими для інтерпретації сучасних трендів зниження рівнів, розуміння синергії регіональних і локальних чинників.

Досліджене питання рівневого режиму озер та чинників, що на нього впливають, у закордонній науковій літературі. Такі праці визначають науковий фон вивчення рівневого режиму озер світу та дають методологічні орієнтири для аналізу його на прикладі оз. Світязь. Статті, присвячені гідрології та морфометрії озерних систем у контексті кліматичних змін [12], тенденціям рівня води Великих озер Північної Америки під впливом змін клімату [13], використанню кліматичних прогнозів для гідрологічного моделювання [15; 23], визначають ключові механізми формування динаміки рівнів води озер в умовах глобального потепління. Одним із основних методів відстеження змін в озерних гідроекосистемах є методи ДЗЗ [14]. Дослідження ролі підземного живлення в озерних системах [16], впливу рекреації на якість води [22] формують концептуальні засади аналізу водного балансу Світязя з урахуванням його складного походження та особливостей антропогенного впливу.

Окремим методичним блоком досліджень є розробка та імплементація сучасних моделей прогнозування рівнів води – від нейромережевих і гібридних алгоритмів [17; 18] до байєсівських та регіональних моделей водного балансу [25; 26]. Такі підходи забезпечують можливість створення точних багатофакторних моделей змін рівня, що виглядає перспективним для Світязя за умови обмеженості інструментальних спостережень. Дослідження екологічно мінімальних рівнів у мілководних озерах [24] і взаємозв'язків вмісту солей у воді та рівня озер [27] відкривають нові підходи до розробки моделей управління рівневим режимом озера в умовах змін клімату та гідрологічного навантаження. Важливими для нас були також публікації про вплив клімату й антропогенних чинників на ґрунтові води [28], екстремальні екологічні події у водоймах [33], оскільки вони актуальні для аналізу ризиків різких знижень рівня Світязя.

Виділення невирішених раніше частин загальної проблеми. Озеро Світязь є складною

гідрологічною системою, рівневий режим якої визначається особливостями поєднання атмосферного, поверхневого та підземного живлення. Незважаючи на наявність окремих досліджень по батиметрії, гідрохімічних особливостях, евтрофікації, результатах дистанційного моніторингу, стан досліджень озера досить фрагментарний. Не вистачає кількісної оцінки внеску підземних вод в структуру водного балансу озера, інтегрованих моделей водного балансу та систематичних даних про особливості антропогенного впливу. Недостатньо вивченою є реакція гідроекосистеми озера на коливання рівня води, верифікація локальних вимірювань із даними ДЗЗ, вплив зміни клімату на рівень води та водний баланс озера. Ці прогалини обмежують можливості для прогнозування, оцінки стійкості гідроекосистеми озера та розробки заходів сталого управління озером та його водозбірною територією.

Метою дослідження є наукове обґрунтування особливостей формування, виділення сучасних тенденцій та чинників зміни рівневого режиму озера Світязь на основі аналізу гідрометеорологічних параметрів, елементів водного балансу озера та просторово-часових закономірностей їх коливань.

Матеріали та методи

Для проведення досліджень використані матеріали Волинського центру з гідрометеорології (середньомісячні рівні води оз. Світязь з 1970 по 2024 р., середньомісячні температури та кількість опадів за той же період). Автори висловлюють щиру вдячність колективу та адміністрації Волинського центру з гідрометеорології за надані матеріали. А також датасет із числами Вольфа, що характеризують сонячну активність, взятий з сайту Solar Influences Data Analysis Center [32].

Методика проведення дослідження передбачала послідовну реалізацію декількох етапів. На першому етапі всі дані зібрані в єдину базу. Проведена їх попередня перевірка на наявність пропусків, аномальних («вистрибуючих») або некоректних значень. Наступний аналіз спрямований на дослідження динаміки рівня води. Побудова графіків та базові статистичні процедури дозволили виявити довготривалі тенденції, зокрема, встановити, чи озеро стабільне за розмірами внаслідок коливання рівнів, чи спостерігається його обміління тощо. Визначено сезонні коливання шляхом обчислення середніх значень рівня води для кожного місяця протягом досліджуваного періоду.

Для встановлення синхронності зміни рівня води з змінами метеорологічних параметрів, реакції гідроекосистеми озера на теплі та сухі роки, впливу сонячної активності на гідрологічні процеси через кліматичні механізми використано кореляційний аналіз. Окрему увагу приділено визначенню років із критичними максимумами та мінімумами рівнів води. Вони зіставлені з погодними умовами та фазами сонячних циклів, що дозволило краще зрозуміти чутливість озера до зовнішніх впливів. На підсумковому етапі отримані результати узагальнені для оцінки багаторічної динаміки рівневого режиму озера Світязь та визначення ключових чинників його змін у контексті кліматичних коливань і антропогенного впливу.

Результати

Аналіз графіка багаторічних коливань середньорічних величин рівня води (рис. 1) показує, що протягом періоду спостережень (1970-2024 рр.) середньорічний рівень води озера зазнавав значних і нерегулярних коливань.

Рівні води змінювалися в широкому діапазоні – від 98 до 178 см. Лінійний тренд на графіку показує повільне, але стале зростання рівня води з часом (від 131 см в 1970 р. до 145 см у 2024 р.).



Рис. 1. Динаміка середньорічних рівнів води озера Світязь, см
Fig. 1. Trends in average annual water levels of Lake Svityaz, cm

З графіка (рис. 1) видно, що динаміці рівнів властивий чітко виражений цикл тривалістю 10-15 років. Найвищі значення рівнів води за досліджуваний період спостерігалися наприкінці 1970-х – на початку 1980-х рр., на межі 1990–2000 рр., всередині 2010-х рр., в 2023–24 рр. Найбільші зниження рівнів зафіксовано у середині 1970-х рр., на початку 1990-х та у 2019-21 рр., коли рівень води озера знизився майже до мінімуму.

Мінімальні із розрахованих середньорічних величин рівня води зафіксовано в 1972 р. (98 см), 1973 р. (103 см). Проте найбільшого суспільного розголосу набули не ці значення, а рівень 2020 р. (107 см) та 2019 р. (114 см). Хоча це й не були мінімальні значення із середньорічних, рівні води не перевищували 98 см протягом з серпня 2019 р. до січня 2020 р., далі рівень почав відновлюватись.

Максимальні значення середньомісячних величин рівня води відмічені в 1981 р. (178 см), 1982 р. (168 см), 2023 р. (163 см). Зокрема, з січня до квітня 1981 р. рівень води перевищував 184 см, за той же ж період 1982 р. – 185 см, у 2023 р. зафіксовано лише рівень 170 см в квітні-травні, а в 2024 р. – 181 см – в березні квітні. Загалом в наш час рівні води дещо нижчі і зміщені на весну.

Особливо помітними на графіку є відносно короткі періоди різких змін: швидке підвищення у 1975-81 рр., суттєве зниження після 1981 р., у 2016-20 рр., яке завершилося дуже швидким відновленням у 2020-23 рр. Це свідчить про значну чутливість водного балансу озера до метеорологічних параметрів, особливостей формування стоку та гідрологічних умов, можливий вплив багаторічних атмосферних циклів і циклів сонячної активності.

Поліноміальна апроксимація (рис. 1) показує, що в багаторічному коливанні рівнів води можуть чітко видні циклічні закономірності. Також чітко проявляється вплив нерегулярних або зовнішніх чинників, що виражається в динаміці періодичною складовою. Повільне підвищення середнього рівня води на тлі багаторазових коливань, яке в цілому простежується по графіку, зумовлене високими рівнями в 2023-24 рр., меншою мірою в 2007-11 рр.

Для гідрологічного режиму озера властиві періодичні багаторічні цикли, що супроводжуються різкими коливаннями рівня, пов'язаними зі зміною режиму опадів та зливового стоку, дією інших природних чинників.

Важливо також проаналізувати коливання рівнів води в розрізі окремих місяців. На рис. 2 зображено графік багаторічної динаміки середніх місячних рівнів озера. Його аналіз дозволив виділити наступні тенденції.

– по всіх місяцях простежується подібна послідовність зміни рівнів;

– рівень озера має виражений хвилеподібний характер, що підтверджує тезу про природну циклічність і міжрічні коливання;

– спостерігається суттєвий міжрічний розкид даних;

– чітка монотонна тенденція (постійне зростання чи спадання рівня) відсутня, графік демонструє довготривалий цикл зі змінною амплітудою;

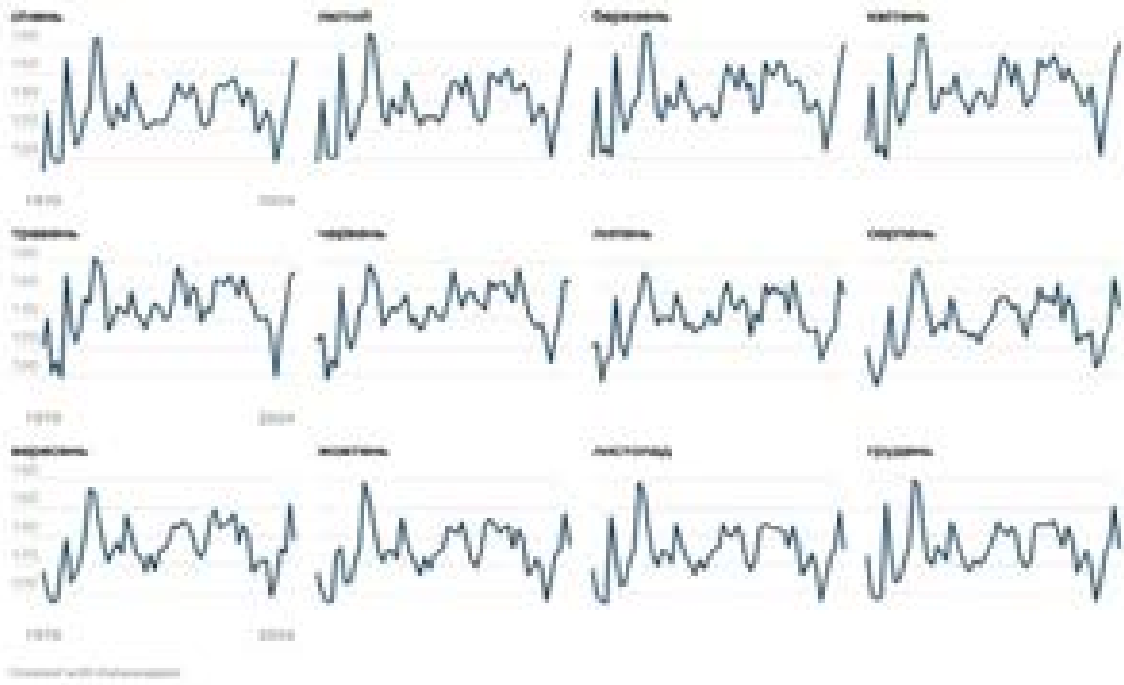


Рис. 2. Графічна візуалізація багаторічної динаміки середніх місячних рівнів озера (побудовано з використанням онлайн-інструменту Datawrapper)
Fig. 2. Graphical visualization of long-term dynamics of average monthly lake levels (created using the Datawrapper tool)

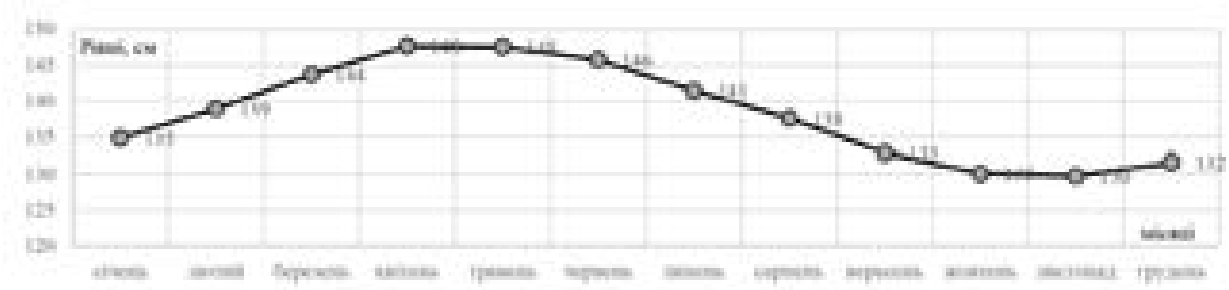


Рис. 3. Середні багаторічні місячні рівні води протягом року /
Fig. 3. Average long-term monthly water levels throughout the year

– у 2023-24 рр. простежується різкий підйом графіка, що може свідчити про екстремально високий рівень води в озері в останні роки.

Детальний аналіз графіка (рис. 2) дозволяє виділити особливості сезонів. Наприклад, протягом зимових місяців рівні демонструють найрізкіші міжрічні коливання, глибокі падіння та короткі високі піки. Навесні характер коливань дещо подібний до зимового, але амплітуда більш згладжена. У травні чітко виділяються періоди відносно вищих рівнів. Влітку динаміка стійкіша, зміни менш різкі, а рівні коливаються у стабільніших межах. Восени знову спостерігаються помітніші коливання, подібні до зимового періоду, амплітуда їх збільшується, різкі піки трапляються частіше.

Графік (рис. 3) демонструє класичну сезонну криву рівня озера**,** яка відбувається за наступним сценарієм: підвищення взимку → весняний максимум → літнє плато → осіннє падіння → зимове відновлення.

Такі закономірності рівневого режиму характерні для оз. Світязь, оскільки його режим визначається таненням снігу, кількістю опадів, температурним режимом, інтенсивністю випаровування. Рівень озера найвищий навесні (квітень-травень) і найнижчий восени (жовтень-листопад). Основними тенденціями при цьому є:

1. Поступове підвищення рівнів з січня до квітня. За середніми багаторічними даними рівень води від січня до квітня піднімається на 14 см, що пояснюється таненням снігу й збільшенням поверхневого притоку.

2. Пік рівнів досягається в квітні (середній багаторічний – 149 см), що відповідає періоду найбільш інтенсивного весняного стоку.

3. Протягом травня-червня відбувається легка стабілізація до рівня 146 см. При цьому рівень майже не змінюється, зберігається плато рівнів. Це період, коли озеро ще добре наповнене, а випаровування не досягло максимуму.

4. Протягом другої половини літа і аж до осені (липень-листопад) рівень озера поступово знижується, найбільше падіння фіксується восени через інтенсивне літнє випаровування, зменшення кількості опадів та поверхневого притоку.

5. Мінімальні рівні властиві у жовтні–листопаді (130 см) і пов'язані з завершенням сезону дощів, ще досить високим випаровуванням, низьким поверхневим притоком води.

6. В грудні фіксується невелике зростання рівнів через початок зимових опадів і зменшення випаровування через холод. Воно знаменує перехід до нового витка річного циклу.

В цьому контексті особливо цікавим виглядає аналіз динаміки рівнів води у екстремальні місяці, тобто за найвищого і найнижчого рівня (рис. 4).

Як видно з рис. 4, для динаміки рівнів води досліджуваного озера властиве поєднання довго-

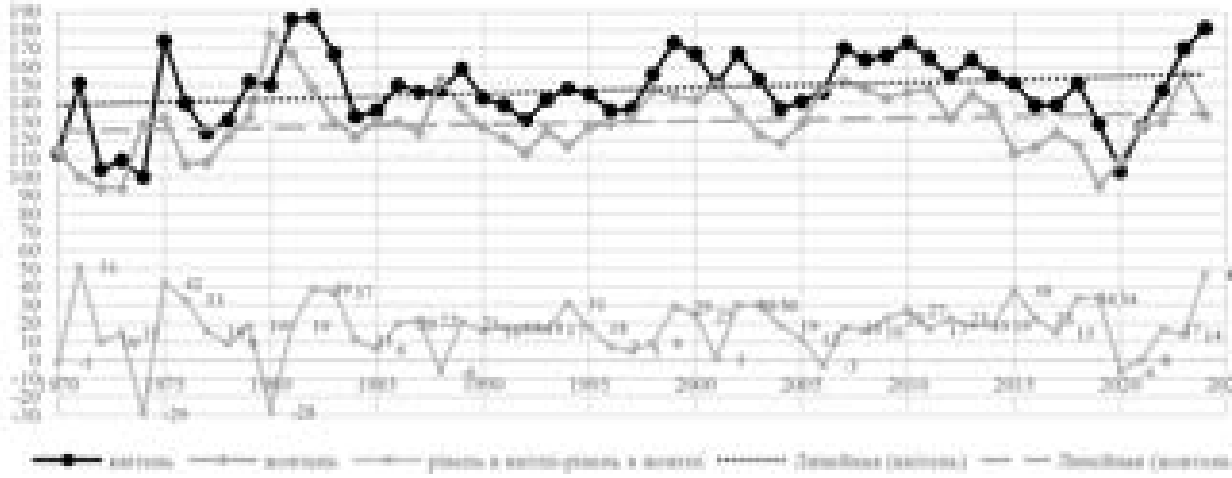


Рис. 4. Динаміка рівнів води у екстремальні місяці та різниці між ними /
Fig. 4. Water level dynamic in extreme months and differences between them

строкових слабких трендів із виразною міжрічною мінливістю. Це свідчить про чутливість лімносистеми до кліматичних флуктуацій. Амплітуда значень між весняним і осіннім рівнями в окремі періоди – це індикатор змін у режимі випадання опадів, температурі та випаровуванні, а також впливі антропогенних чинників у басейні.

Причиною високих весняних рівнів води є природний гідрологічний режим з максимумом, зумовлений сніготаненням і весняними опадами. Значенням рівнів в квітні властиві значна міжрічна мінливість – спостерігаються як різкі максимуми (кінець 1970-х рр., початок 1980-х рр., окремі роки після 2000 р.), так і глибокі мінімуми (середина 1970-х рр., 2019-21 рр.). Лінійний тренд для квітня має слабко позитивний нахил, що свідчить про загальну тенденцію до незначного підвищення весняних рівнів у довгостроковій перспективі (від 140 до 155 см).

Осінні рівні води нижчі, але теж демонструють істотну міжрічну варіабельність. Аномально низькі значення зафіковані у 2000-х рр., наприкінці 2010-х рр. пов'язані з тривалими маловодними періодами та дефіцитом опадів у теплий сезон. Лінійний тренд рівнів жовтня є пологішим ніж для квітня, ближчим до нейтрального, з тенденцією до слабкого зростання або стабілізації рівнів (з 125 до 133 см).

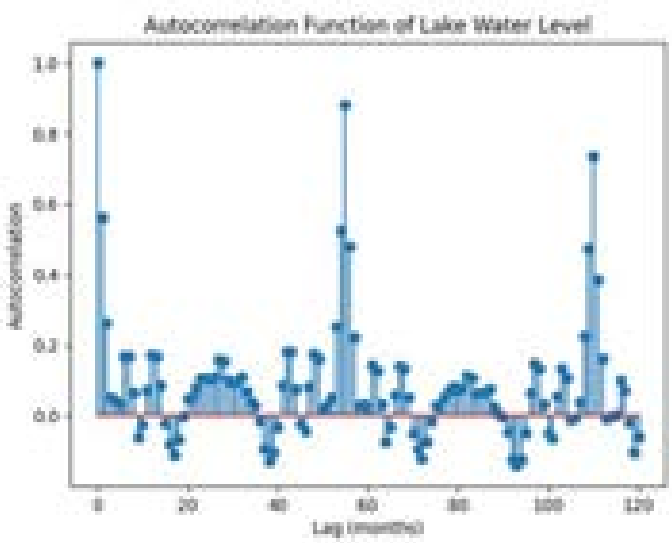


Рис. 5. Автокореляційна функція рівнів води озера /
Fig. 5. Autocorrelation function of lake water levels

Різниця максимальних і мінімальних рівнів по місяцях протягом більшості років додатна, що свідчить про суттєвість весняного максимуму у ці роки. Але в той же ж час амплітуда різниці значно коливається: від майже нульових і навіть від'ємних значень (в окремі роки, коли жовтневий рівень дорівнює або вище квітневого) до різко позитивних піків (40-50 см). Наприклад, амплітуда була максимальною додатньою в 1970 р. (+51 см), 1975 р. (+42 см), 2024 р. (+48 см), максимальною від'ємною в 1974 р. (-29 см), 1980 р. (-28 см). Загалом за усі роки спостережень від'ємних значень амплітуди було суттєво менше (приблизно 9%). Це є індикатором контрастних гідрологічних умов року. Аналіз динаміки різниці рівнів свідчить, що попри значну амплітуду коливань у 1970–1980-х рр., сучасний період характеризується частим чергуванням маловодних років із глибокими мінімумами (наприклад, 2019–2021 рр.). Хоча загальна дисперсія ряду в останні десятиліття не демонструє статистично значущого зростання порівняно з початком спостережень, частіша поява екстремальних значень свідчить про зміщення сезонних максимумів та трансформацію традиційної структури гідрологічного режиму».

Аналіз закономірностей рівнового режиму озера дозволив виділити основні гідроекологічні ризики. Найбільш ймовірними серед них є:

1. Ризик мілководіння та деградації літоралі. Екстремально низькі рівні озера у жовтні, особливо у 1972 р., 1973 р., 2019 р. становили 90-95 см, це є індикатором підвищеної ймовірності скорочення площі літоральної зони, оголення донних відкладів і вторинного запилення берегів, деградації прибережно-водної рослинності. Для озера така ситуація може бути критичною, оскільки літораль є ключовою зоною біопродуктивності та самоочищення.

2. Посилення сезонної нестійкості гідрологічного режиму. Суттєва міжрічна мінливість амплітуди між весняним і осіннім рівнями свідчить про зниження стабільності водного балансу, порушення усталеного сезонного ритму наповнення й спрацювання озера, що створює ризики для гідробіонтів, життєві цикли яких пов'язані із сезонними рівневими фазами.

3. Ризик евтрофікації та «цвітіння» води. Зниження рівня води пов'язано із зменшенням об'єму води в озері. А це в свою чергу підвищує концентрацію біогенних елементів, температуру води, інтенсивність розвитку фітопланктону та ціанобактерій [22]. Тому зростає ризик евтрофікації озера у маловодні роки.

4. Дестабілізація донних процесів. Різкі коливання рівнів, зокрема, різкі весняні підйоми рівнів та глибокі осінні спади сприяють періодичному пересиханню та повторному затопленню донних відкладів, повернення у воду сполук фосфору та органічих речовин, задепонованих у озерному мулі, погіршенню кисневого режиму.

5. Зниження екологічної стійкості озера. Зростання амплітуди коливань і частоти екстремальних років свідчить про підвищену чутливість озера до кліматичних коливань, знижену буферну здатність гідроекосистеми, ризик переходу озера у гірший, менш стабільний екологічний стан.

На рис. 5 зображений графік автокореляційної функції рівнів води озера. З графіка видно, що досить великим є значення автокореляції при лагу 1 місяць (≈ 0,56). А це свідчить, що рівень води сильно залежить від особливостей попереднього місяця, тобто про інерційність лімносистеми. Помітний також пік на лагу 12 місяців, повторювані підвищення кореляції біля 12 місяців, 24 місяців, далі слабше. Це виділяє сезонність з періодом 1 рік. Амплітуда автокореляційної функції зменшується з лагом, довготривала стабільна кореляція відсутня, що типово для квазіперіодичних процесів. Також відсутні виражені піки на 36, 48, 60 місяців. Отже, автокореляційна функція не дозволяє однозначно підтвердити довгий (декількарічний) цикл коливань рівнів.

Для кількісного визначення домінантних періодів (циклів) у часовому ряді середньомісячних рівнів води використано метод спектрального аналізу. В основі методу лежить швидке перетворення Фур'є. На рис. 6 представлено періодограму (оцінку спектральної густини потужності) для часового ряду середньомісячних рівнів води, обчислену на основі 660 спостережень (55 років).

Періодограма показує, що найбільша потужність зосереджена у короткому (річному) циклі, довгі хвилі є другорядними. Це типовий результат для багатьох природних процесів, де річна сезонність переважає над багаторічними трендами. На графіку можна ідентифікувати кілька чітко виражених піків. Найбільш потужний пік із них має частоту 0,0833 циклів на місяць (період 12 місяців). Для нього властива найвища амплітуда серед усіх компонент. Отже, річна сезонність є домінуючим фактором коливання рівня води в озері. Гідрологічно це пояснюється річним циклом опадів, таненням снігу та випаровуванням. Другий за потужністю пік має частоту 0,009 циклів на місяць, що відповідає періоду приблизно 9,26 року. Він свідчить про значущу багаторічну складову в динаміці рівня води, яка, ймовірно, пов'язана з кліматичним циклом або циклами сонячної активності. Третій пік має найнижчу частоту 0,0015 циклів на місяць (період 55,56 років) і відображає тренд за весь період спостережень. Він має низьку потужність порівняно з річним циклом, але все ж є значущим.

Після ідентифікації домінантних періодів (1 рік та 9,26 року) перевірена їх статистична значущість. Для цього застосовано критерій Фішера для періодограми (g-критерій Фішера). Нульова гіпотеза (H_0) сформульована наступним чином: часовий ряд є випадковим білим шумом, всі частоти мають однакову очікувану потужність, виявлені піки є випадковими флуктуаціями. Альтернативна гіпотеза (H_A) каже, що часовий ряд містить принаймні одну значущу гармонічну складову (період), що відрізняється від шуму. Розрахунки g-критерій Фішера (табл. 1) підтвердили, що виявлені за допомогою періодограми цикли є статистично значущими. Розрахований для моделі коефіцієнт детермінації (R^2) становить 0,778. Це досить значний показник, як для процесу, на який впливає дуже багато чинників.

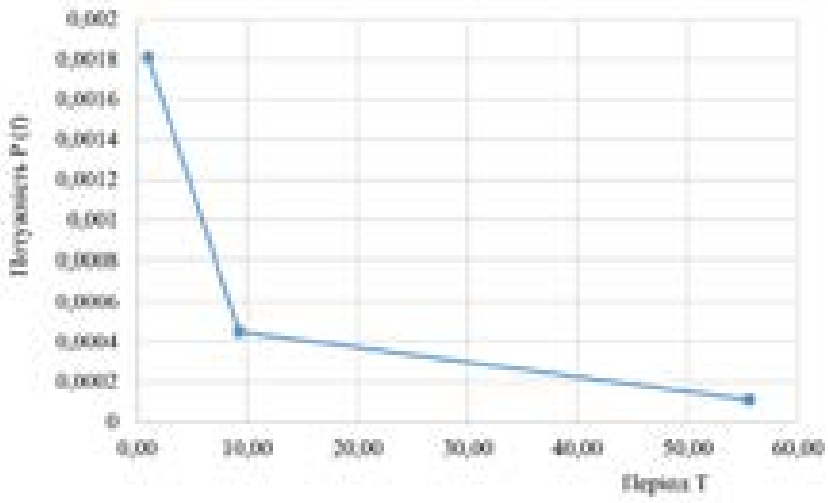


Рис. 6. Періодограма часового ряду середньомісячних рівнів води / **Fig. 6.** Periodogram of the time series of average monthly water levels

Таблиця 1 / Table 1

Результати розрахунку g-критерій Фішера / Results of Fisher's g-test calculation

Період, T (роки)	Розрахункове g	Критичне g_{crit}(α=0.05)	Значущість
1	12,07	≈ 0,05	Значущий
9,26	3,10	≈ 0,05	Значущий

Декомпозиція часового ряду рівнів води озера дозволяє виділити тренд-циклічну, періодичну та неперіодичну складові (рис. 7). Тренд-циклічна складова коливається навколо виділеного багаторічного періоду зміни рівнів (9,26 років), накладеного на середній рівень (134,8 см). Це свідчить про відсутність різкого лінійного зростаючого або спадаючого тренду за період спостереження. Періодична складова являє собою практично ідеальну синусоїду з періодом 12 місяців. Вона демонструє, що рівень води щороку коливається за дуже схожим і передбачуваним сценарієм. Неперіодична

складова (флуктуація, залишкова компонента) – це невстановлена варіація, отримана після віднімання всіх змодельованих систематичних компонент. Вона показує, що більша частина дисперсії була пояснена моделлю. Залишок зосереджений навколо нуля і має вигляд слабко корельованого шуму.

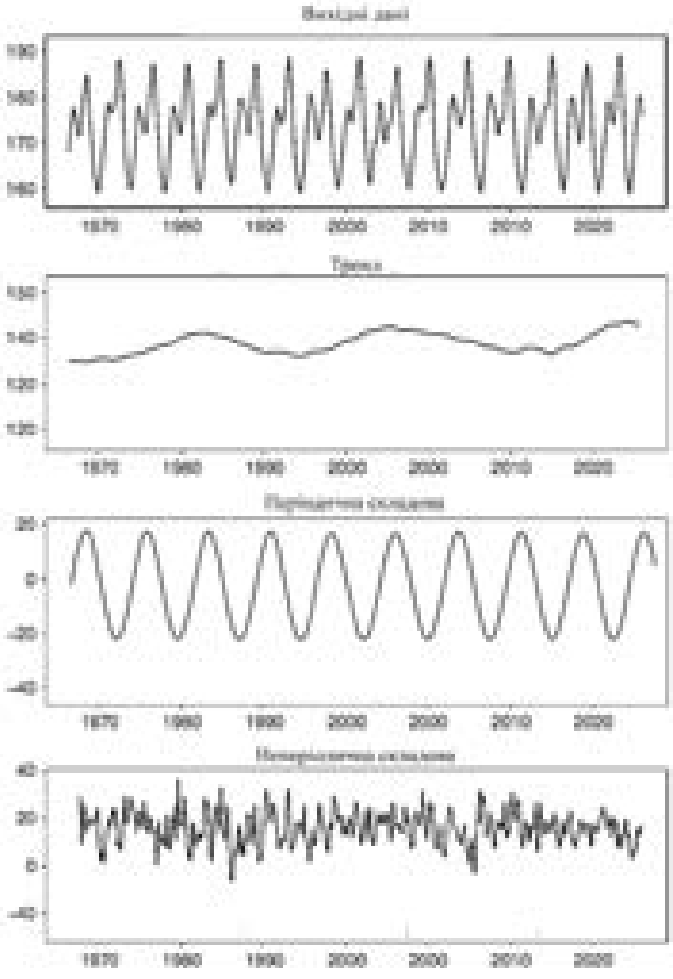


Рис. 7. Декомпозиція часового ряду рівнів води озера
Fig. 7. Decomposition of the time series of lake water levels

На рис. 8 та у табл. 2 наведені результати кореляційного аналізу рівнів води (середніх місячних рівнів, середніх за рік, всього масиву по місяцях за рік) та опадів (середніх за місяць, рік). Тільки за вересень зв'язок помірний (середній), за лютий, квітень, червень-серпень, листопад, грудень і за рік зв'язок слабкий, в усі інші місяці – дуже слабкий.

Розраховані коефіцієнти кореляції перевірені на статистичну значущість (табл. 2). Для цього використано t-критерій Стьюдента. Обсяг вибірки становить 55 років, рівень значущості $\alpha = 0{,}05$, число ступенів свободи $df = n - 2 = 55 - 2 = 53$. За таких умов $t_{табл}$ становить приблизно 2,0057. Якщо $|t_{емп}| \geq 2{,}0057$, коефіцієнт кореляції статистично значущий. На рівні значущості $\alpha = 0{,}05$ статистично достовірними (значущими) є коефіцієнти кореляції лише для квітня та вересня. Дуже близьким є також коефіцієнт за листопад. Усі інші коефіцієнти (в т.ч. річний $r = 0{,}12$) є статистично незначущими, тобто відсутні підстави стверджувати про існування лінійного зв'язку в генеральній сукупності. Це наштовхує на думку, що статистично значущим є зв'язок для місяців із естремальними (максимальними та мінімальними) рівнями – квітня та жовтня, в околі якого якраз і є вересень та листопад. Отже, оскільки щільність зв'язку між опадами та рівнями не висока, то сама по собі кількість опадів не є чинником, що визначає рівень озера.

Аналогічно розраховані коефіцієнти й між рівнями води (середніми місячними рівнями, середніми за рік) та температурою повітря (середньою за місяць, рік). Результати представлені на рис. 9 та у табл. 3. Помірний (середній) зв'язок

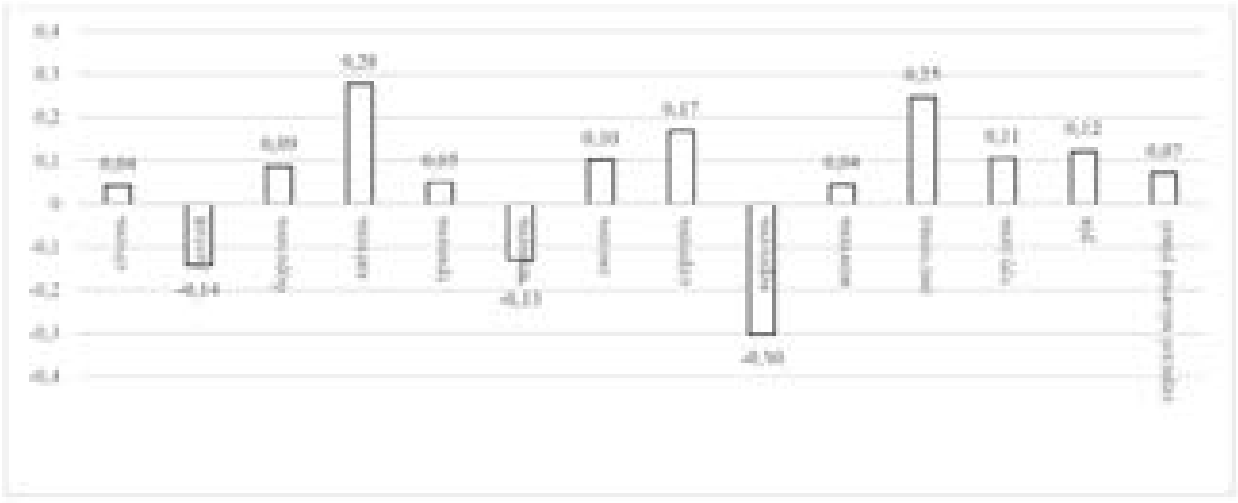


Рис. 8. Коефіцієнти кореляції між рівнем води та опадами /
Fig. 8. Correlation coefficients between water level and precipitation

Таблиця 2 / Table 2

Результати кореляційного аналізу / Results of correlation analysis

Місяць	r	temp	Статистична значущість	Сила зв'язку
січень	0,04	0.3063	не значущий	Дуже слабкий
лютий	-0,14	-1.0517	не значущий	Слабкий
березень	0,09	0.6296	не значущий	Дуже слабкий
квітень	0,28	2.1769	значущий	Слабкий
травень	0.05	0.3593	не значущий	Дуже слабкий
червень	-0,13	-0.9503	не значущий	Слабкий
липень	0,10	0.7367	не значущий	Слабкий
серпень	0,17	1.2504	не значущий	Слабкий
вересень	-0,30	2.3825	значущий	Помірний (Середній)
жовтень	0,04	0.3197	не значущий	Дуже слабкий
листопад	0,25	1.9397	не значущий	Слабкий
грудень	0,11	0.8927	не значущий	Слабкий
рік	0,12	0.8927	не значущий	Слабкий
середні місячні рівні	0,07	0.5225	не значущий	Дуже слабкий

характерний лише для травня, для інших місяців – слабкий. Хоча сила зв'язку між рівнями та температурою суттєво вища, ніж між рівнями та опадами.

За рівня значущості α = 0,05 статистично достовірним (значущим) є коефіцієнт кореляції лише для травня. В усі інші місяці статистична значимість не підтвердилась. Це закономірно, оскільки статистична значущість пов'язана із силою зв'язку. Температура повітря визначає величину випаровування і, на перший погляд здається, що саме в травні вона помірно пов'язана із формуванням рівня води. Але температура в цій моделі діє як тригер танення, а не як чинник випаровування.

Підсумовуючи взаємозв'язок рівнів води і метеорологічних параметрів території слід відмітити, що озеро чітко реагує на весняні опади (квітень) підвищенням рівня, хоча й зі слабкою силою зв'язку. Восени вплив опадів стає оберненим, що свідчить про переважання випаровування або інших чинників (наприклад, впливу водозабору) у цей сезон. Гідрологічний режим озера найчутливіший до кліматичних факторів у весняно-осінній перехідний період (квітень, травень, вересень), а не протягом основних сезонів (літа чи зими). Рівень води визначається інтенсивністю весняного стоку та сукупним ефектом літніх втрат. Зв'язок між рівнем і кліматичними показниками в більшості місяців є слабким та статистично недостовірним. Це є ознакою складності гідрологічної системи, в якій, крім опадів і температури, важливу роль відіграють інші, в т.ч. невраховані чинники (ґрунтові та підземні води, водозабір, тощо).

Врахування впливу кліматичних чинників на рівень озера останнім часом ускладнене їх зміною в останні десятиліття (рис. 10, 11). Вона впливає на рівень води в озері Світязь, зміщуючи гідрологічний баланс у бік втрат. Це під-

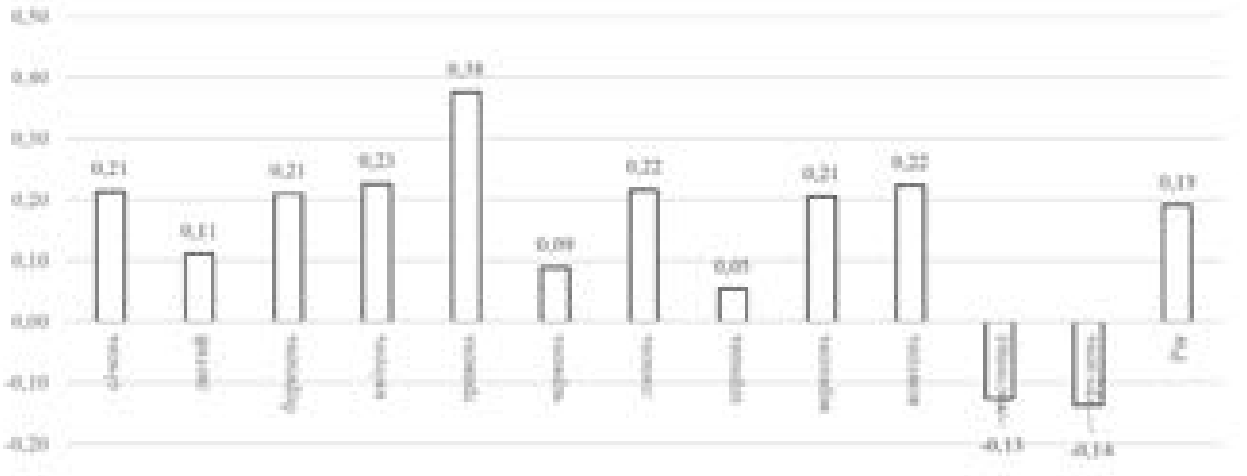


Рис. 9. Коефіцієнти кореляції між рівнем води та температурою повітря
Fig. 9. Correlation coefficients between water level and air temperature

Таблиця 3 / Table 3

Результати кореляційного аналізу / Results of correlation analysis

Місяць	r	t_{emp}	Значущість	Сила зв'язку
січень	0.21	1.5770	Не значущий	Слабкий
лютий	0.11	0.8109	Не значущий	Слабкий
березень	0.21	1.5495	Не значущий	Слабкий
квітень	0.23	1.6667	Не значущий	Слабкий
травень	0.38	2.9969	Значущий	Помірний (середній)
червень	0.09	0.6504	Не значущий	Слабкий
липень	0.22	1.5970	Не значущий	Слабкий
серпень	0.05	0.3925	Не значущий	Слабкий
вересень	0.21	1.5110	Не значущий	Слабкий
жовтень	0.22	1.6541	Не значущий	Слабкий
листопад	-0.13	0.9231	Не значущий	Слабкий
грудень	-0.14	1.0084	Не значущий	Слабкий
Рік	0.19	1.4097	Не значущий	Слабкий

тверджують кореляційні зв'язки між рівнем озера і метеорологічними параметрами. Зокрема, зростання температури посилює випаровування. Хоч цей процес лінійно не корелює з рівнем води влітку, але його акумулятивний ефект є настільки суттєвим, що переважає надходження води в озеро. Про це свідчить обернений достовірний зв'язок у вересні. Зміна клімату змінила режим їх випадання. Дефіцит опадів у теплий період разом із підвищенням температури зумовлює ситуацію, коли річні показники водного балансу стають від'ємними, а рівень води знижується через неможливість компенсації літніх втрат. Малі значення коефіцієнтів кореляції свідчать про те, що кількість опадів у певний момент часу не впливає на рівень води в озері, минулорічні опади більше впливають на зміну рівня води [2]. Також це є свідченням суттєвості впливу на рівень води не лише клімату і його зміни, але й діяльності людини (використання підземних вод, меліорація). Причому саме вплив цього чинника посилюється в умовах кліматичного стресу.

Ще одним аспектом, що викликає науковий інтерес, є ймовірний зв'язок рівнів води із соняч-

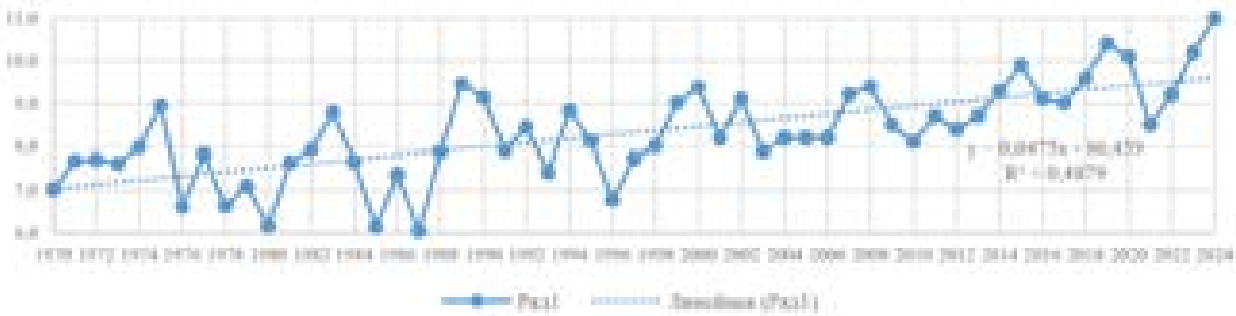


Рис. 10. Динаміка середньорічної температури повітря по МС Світязь за 1970-2024 рр. /
Fig. 10. Trends in the average annual air temperature in the Svitiaz MS for 1970-2024

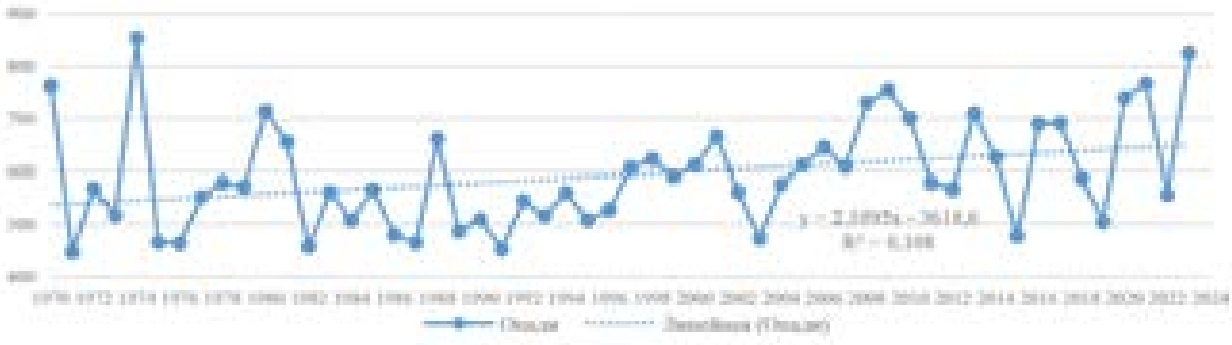


Рис. 11. Кількість опадів по МС Світязь за 1970-2024 рр. /
Fig. 11. Amount of precipitation in the Svitiaz meteorological station for 1970-2024

ною активністю. Вона циклічна. Найвідомішим є 11-річний сонячний цикл (цикл Швабе) із періодами сонячного максимуму та мінімуму. Сонячні цикли можуть впливати на клімат через зміну атмосферної циркуляції, яка визначає траєкторії циклонів і антициклонів над Східною Європою. Циклічні зміни сонячної активності можуть бути одним із природних кліматичних драйверів, що підсилюють (або пом'якшують) сезонну асиметрію водного балансу, спричинену зміною клімату. Для розрахунків використано числа Вольфа – міру кількості сонячних плям і груп сонячних плям на поверхні Сонця, за допомогою яких відстежується активність Сонця та 11-річного циклу сонячної активності. Безпосереднього і загальновизнаного зв'язку між числами Вольфа та рівнем води в конкретному озері не існує. Проте, в ряді досліджень зустрічаються гіпотези або твердження про те, що динаміка сонячної активності, виражена через числа Вольфа, може опосередковано впливати на рівень води в озерах. Зокрема, через зміни в глобальних і регіональних кліматичних та гідрологічних процесах. Наприклад, у роботі [33] досліджено вплив сонячної активності на режим оз. Вікторія.

Тому проведено кореляційний аналіз середніх місячних рівнів оз. Світязь та чисел Вольфа за період 1970-2024 рр. Коефіцієнт кореляції r = 0,084286 є статистично значущим на рівні α = 0,05. Значення коефіцієнта пряме, але дуже низьке, що відповідає дуже слабкій кореляції. Значний обсяг вибірки (660 місяців) дозволяє стверджувати, що цей невеликий зв'язок не є випадковим та існує в генеральній сукупності. Тобто цикли сонячної активності впливають на рівні озера дуже слабо.

Зіставлення фаз сонячного циклу з аномаліями рівня води дозволило зробити висновок, що підвищення сонячної активності може дуже слабко корелювати з зниженням рівня води (r = -0,11) приблизно через 18-24 місяці. Спектральний аналіз даних зниження рівня води не показує чіткого 11-річного циклу, властивого сонячній активності. Це підтверджує, що вона не є домінуючим чинником формування рівнів води.

Одним із чинників, що впливає на рівні і проявляється на водозборі озера є господарська діяльність. Зокрема, активне меліоративне освоєння території, використання води для зрошення багаторічних культур (ягід), самовільне спорудження ставків-випаровувачів для зниження рівня грунтових вод на приватних ділянках, необліковуване добування підземних вод, потенційний вплив Хотиславського крейдового кар'єру.

Дискусія і висновки

Дослідження рівневого режиму оз. Світязь підтвердили його високу чутливість до дії метеорологічних чинників. Протягом періоду спостережень (1970-2024 рр.) рівні води коливались в широкому діапазоні значень, від критичних мінімумів до аномально високих рівнів. Річна сезонність є домінуючим чинником формування рівневого режиму, але на фоні річних циклів простежуються багаторічні хвилі з періодом 9,26 років. Виявлена тенденція засвідчила поєднання короткострокових закономірностей із довготривалими флуктуаціями, що й визначає рівневий режим озера.

Протягом екстремальних періодів (1972-73 рр., 2019-21 рр., 2023-24 рр) рівні води досягали критичних мінімумів або, навпаки, різко зростали. Такі коливання сприяють формуванню гідроекологічних ризиків. Зокрема, мілководдя, деградації літоралі, нестійкості сезонного режиму, евтрофікації та «цвітіння» води, дестабілізації донних процесів. Статистично виявлена тенденція зростання амплітуди між весняними та осінніми рівнями є ознакою зниження буферної здатності лімносистеми й підвищення її вразливості.

Кореляційний аналіз розкрив відносно слабкий зв'язок рівнів води з кількістю опадів. Це свідчить про багатофакторність процесів живлення озера, значну роль ґрунтових та підземних вод у цьому процесі. Навіть за відносно стабільної кількості опадів можуть відбуватись різкі коливання рівнів води через внутрішні гідрологічні механізми. Повільне проникнення поверхневого живлення до грунтових вод та глибших водоносних горизонтів, а також антропогенна діяльність збільшують часовий лаг впливу опадів на рівень води в озері.

Отримані результати дозволяють зробити кілька ключових висновків:

– рівневий режим озера Світязь відображає накладання сезонних і багаторічних коливань гідрологічних та метеорологічних параметрів;

– сучасні тенденції свідчать про збільшення нестійкості лімносистеми та ризик її переходу до менш стабільного стану;

– для збереження екологічної стійкості необхідний постійний гідроекологічний, гідрологічний, гідрогеологічний та меліоративний моніторинг, моделювання сценаріїв змін лімносистеми та розробка заходів її кліматичної адаптації.

Внесок авторів: всі автори зробили рівний внесок у цю роботу
Конфлікт інтересів: автори повідомляють про відсутність конфлікту інтересів

Декларація про використання генеративного штучного інтелекту: Автори використовували інструменти генеративного штучного інтелекту (GenAI) для допоміжної роботи: Gemini та DeepL було залучено для перевірки правильності перекладу з однієї мови на іншу та під час оформлення списку використаних джерел. Усі результати роботи з цими інструментами були ретельно контрольовані, перевірені та, за необхідності, відредаговані авторами. Автори несуть повну відповідальність за зміст та цілісність публікації.

Authors Contribution: All authors have contributed equally to this work
Conflict of Interest: The authors declare no conflict of interest

Declaration of use of generative artificial intelligence: The authors utilized generative artificial intelligence (GenAI) tools in a supportive capacity: Gemini and DeepL were used to check the accuracy of translations from one language to another and to compile a list of sources used. All outputs from these tools were carefully supervised, reviewed, and, where necessary, edited by the authors. The authors retain full responsibility for the content and integrity of the publication.

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Level regime of Lake Svitiaz

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ABSTRACT

Introduction. Lake Svityaz is the largest and deepest of the Shatsk Lakes, and its water level is determined by precipitation, evaporation, groundwater recharge, and human impact. The most significant drops in the lake's water level occurred in 2019–2020. This complicates forecasting and requires scientifically sound management.
The purpose of article is to scientifically substantiate the peculiarities of the formation, identify current trends and factors of change in the water level regime of Lake Svitiaz based on the analysis of hydrometeorological parameters, elements of the lake's water balance, and the spatial and temporal patterns of their fluctuations.
The object of the study is the level regime of Lake Svitiaz as a result of natural and anthropogenic factors.
The subject of the study is the spatial and temporal features of water level fluctuations, natural and anthropogenic factors that determine the water balance and water level regime of Lake Svitiaz.
Data and methods. The study utilized monthly average water levels of Lake Svityaz, monthly average temperature, and precipitation amounts for 1970–2024, as well as Wolf numbers as an indicator of solar activity. Long-term and seasonal changes in water level were analyzed using graphs and statistical calculations. The main parameters of the seasonal cycle were determined. Correlation analysis was used to assess the relationship between water level and temperature, precipitation, and solar activity. Years with minimum and maximum water levels were identified, and the levels were compared with meteorological conditions and the solar activity cycle. The influence of the main factors affecting the lake's water level regime under conditions of climate variability was analyzed.
Results. It was established that the lake's water level depends most significantly on meteorological conditions. Annual seasonality is the dominant factor in the formation of the water level regime. Against the backdrop of annual cycles, long-term waves with a period of 9.26 years can be observed.
Scientific novelty. Quantitative patterns of the influence of meteorological factors and solar activity on the long-term dynamics of water levels in Lake Svityaz have been established. The parameters of the autocorrelation function of water levels and the correlation coefficients between water levels, precipitation, and air temperature have been calculated, and their statistical significance has been determined. A periodogram of the time series of average monthly water levels has been constructed. A decomposition of the time series of Lake Svitiaz water levels has been performed
Practical significance. The results obtained can be used to develop programs for the sustainable management of the Shatsk Lakes limnosystems, nature conservation measures, monitoring, and adaptation to climate change.

ARTICLE INFO

Manuscript received
17 December 2025

Revised manuscript received
6 May 2026

Manuscript accepted
25 May 2026

Available online
30 May 20267d

Keywords:

lake; lake water levels; level fluctuations; lake level regime; factors affecting lake water levels; lake feeding; underground runoff as a source of feeding; lake water balance; climate change.

In cites: Fesyuk Vasyl, Moroz Iryna (2026). Level regime of Lake Svitiaz. *Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology*, (64), 279–292. https://doi.org/10.26565/2410-7360-2026-64-21 [In Ukrainian]

https://doi.org/10.26565/2410-7360-2026-64-22

УДК 556.06.166 (282.247.324)

Довгострокове прогнозування шарів стоку весняного водопілля річки Десна

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АНОТАЦІЯ

У період весняного водопілля річкою Десна надходять значні об'єми води до Канівського водосховища. Довгострокове прогнозування цих об'ємів дозволяє планувати виробіток електроенергії на Канівській ГЕС, питне та технічне водопостачання, регулювання стоку каскаду дніпровських водосховищ, зрошення, рибальство, водний туризм та відпочинок. За основу концептуальних моделей, а також методик довгострокового прогнозування параметрів весняного водопілля, зазвичай приймають метод водного балансу, який потребує значної кількості гідрометеорологічної інформації на водозбірній території річок. Разом з цим, недоступність гідрометеорологічних даних з російської частини водозбору Десни перешкоджає повноцінному застосуванню методу водного балансу для розроблення методики довгострокового прогнозування об'ємів (шарів стоку) весняного водопілля. Спроби замінити дані наземних спостережень на дані реаналізу (запаси води у сніговому покриві та глибина промерзання ґрунту на водозборі р. Десна), які містяться у базі даних ERA5-Land, виявилися невдалими. У тих випадках, коли гідрометеорологічної інформації недостатньо або вона відсутня чи недоступна, застосовують фізико-статистичні або статистичні методи прогнозування. Отже, у дослідженні розроблена методика довгострокового прогнозування шарів стоку весняного водопілля р. Десна – с. Літки на основі фізико-статистичного методу. Отримане регресійне прогнозне рівняння дозволяє прогнозувати шар стоку весняного водопілля за двома предикторами: мінімальною витратою води у першій та другій декаді лютого та середнім місячним значенням телеконнекційного паттерну poleur у серпні місяці. Перший предиктор характеризує зволоженість ґрунтів водозбору річки і, відповідно, потенційні втрати стоку на інфільтрацію, а другий – синоптичні процеси, які, за нашим припущенням, визначають надходження вологи на водозбір річки у зимово-весняний період. Методика прогнозування має статистичну оцінку якості «задовільно» при допустимій похибці перевірочних прогнозів на рівні 15 мм, визначеній за період 1973-2020 рр. Ймовірність неперевищення допустимої похибки становить 69 %, а відношення середньої квадратичної помилки перевірочних прогнозів ($\overline{S}$) до середнього квадратичного відхилення прогнозної величини ($\overline{\sigma}$), тобто $\overline{S}/\overline{\sigma}$, склало 0,77. Після подовження ряду спостережень за шарами стоку р. Десна – с. Літки за даними спостережень р. Десна – м. Чернігів, допустима похибка зросла до 21 мм, що покращило оцінку якості методики від «задовільної» до «доброї».

ІНФОРМАЦІЯ ПРО СТАТТЮ :

Рукопис надійшов
30 березня 2026

Отримано після рецензування
5 травня 2026

Затверджено до друку
25 травня 2026

Опубліковано онлайн
30 травня 2026

Ключові слова:

весняне водопілля, шар стоку, телеконнекційні індекси та паттерни, водний баланс, фізико-статистичний метод, довгострокове прогнозування, Десна, методика.

Постановка проблеми та аналіз останніх досліджень і публікацій

Аналіз процесів, які відбуваються на басейнах річок у період формування весняного водопілля та чинників, що їх зумовлюють був здійснений зусиллями багатьох учених-гідрологів ще впродовж минулого століття [1, 2]. У їхніх працях встановлено, що шари стоку та максимальні витрати води весняного водопілля залежать від запасів води у сніговому покриві на території водозбору річки, ступеня зволоженості

Як цитувати : Христюк Борис, Шакірзанова Жаннетта (2026). Довгострокове прогнозування шарів стоку весняного водопілля річки Десна. *Вісник Харківського національного університету імені В.Н. Каразіна Серія «Геологія. Географія. Екологія»*, (64), 293–301. https://doi.org/10.26565/2410-7360-2026-64-22

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ґрунту та глибини його промерзання, наявності рослинного покриву та заболоченості, опадів та випаровування впродовж весняного водопілля, втрат на інфільтрацію і заповнення безстічних ділянок водозбору, а також від інтенсивності сніготанення, яка у свою чергу залежить від гідрометеорологічних умов розвитку весняних процесів. Усі перераховані вище чинники входять до рівняння водного балансу весняного водопілля, мм [3]:

$$Y = S + N_s + N - P, \quad (1)$$

де Y – шар стоку весняного водопілля; S – запас води у сніговому покриві; N_s – норма кількості опадів, які випадають на сніговий покрив; N – норма кількості опадів, які випадають на поверхню водозбору після танення снігового покриву; P – сумарні втрати стоку на інфільтрацію, випаровування, затримку у безстічних областях водозбору.

Рівняння водного балансу було покладене в основу методики довгострокового прогнозу шару талого стоку весняного водопілля за даними про максимальні запаси води у сніговому покриві, у сумі з опадами періоду сніготанення, та характеристикою вологопоглинаючої здатності ґрунтів у басейнах річок Десни біля м. Розльоти та м. Чернігова, а також Сейму біля с. Мутин. Ця методика була розроблена науковцями Українського гідрометеорологічного інституту у 1988 році [4]. Загальний шар стоку весняного водопілля у цій методиці розраховувався як сума талого, підземного та дощового стоку (після сходу снігового покриву). Останні дві складові приймалися у вигляді середньої багаторічної величини. Втрати талого стоку на інфільтрацію у ґрунти та поверхневу затримку визначалися у залежності від глибини промерзання ґрунту та його вологості.

На основі вирішення рівняння водного балансу в Українському гідрометеорологічному інституті була розроблена математична, а вірніше, сучасною термінологією, концептуальна модель «СЛОЙ-2», яка використовується в оперативній практиці Українського гідрометеорологічного центру для довгострокового прогнозування шарів стоку весняного водопілля рівнинних річок України [5]. У моделі враховуються процеси промерзання та відтавання ґрунту, зміна зволоженості водозборів, динаміка накопичення снігу і сходу снігового покриву безупинно впродовж зимово-весняного сезону з урахуванням залісеності водозборів. Модель «СЛОЙ-2» дозволяє представляти прогнозні шари стоку у картографічному вигляді, а також у ймовірнісній формі за різними сценаріями розвитку весняних процесів.

У праці Шакірзанової [1] розроблено метод територіального довгострокового прогнозу шарів стоку весняного водопілля на річках рівнинної території України (у басейнах правобережжя Прип'яті, Десни, інших приток Середнього і Нижнього Подніпров'я, Сіверського Дінця, Південного Бугу, річок північно-західного Причорномор'я). В якості методичної бази цього методу прийняті залежності модульних коефіцієнтів шарів стоку від сумарних запасів води у сніговому покриві та весняних опадів, виражених відносно їхнього середнього багаторічного значення для річок, по яких є багаторічні ряди гідрометеорологічних спостережень. Прогнозування весняного стоку здійснюється в методі при передчасному визначенні типу розвитку весняних процесів при використанні багатомірної статистичної моделі дискримінантного аналізу, яка враховує різноманітне сполучення впливів гідрометеорологічних чинників на формування тало-дощового стоку весняного водопілля річок. Кількісні значення прогнозних модульних коефіцієнтів шарів стоку отримуються за регіональними залежностями, а самі величини шарів стоку - шляхом їх помноження на середньобагаторічний шар стоку водопілля. Для басейну р. Десна результати застосування цього підходу показано у праці [6].

Серед закордонних моделей, які застосовуються для довгострокового прогнозування водного стоку річок, відомими є модель SSARR (Streamflow Synthesis and Reservoir Regulation model) та модель HBV (Hydrologiska Byrans Vatten balansavdelning model) [7, 8]. Обидві моделі є концептуальними та розроблені на основі методу водного балансу. Вони дозволяють поділяти водозбір річки на області з урахуванням висоти над рівнем моря, кількості опадів, вологості ґрунту, умов випаровування та транспірації. Обидві моделі моделюють водний стік, який формується як від випадіння дощів на водозбір річки, так і від танення снігового покриву [9, 10]. Для довгострокового прогнозування водного стоку у цих моделях використовуються історичні метеорологічні ряди. Для басейну річки Десна адаптована модель SWAT (Soil and Water Assessment Tool), яка дозволяє прогнозувати гідрограф стоку на основі даних про ґрунти, землекористування, метеорологічні умови тощо [11]. Разом з цим, ця модель використовується для короткострокового та дуже довгострокового прогнозування (декілька десятиліть) [12, 13].

У випадках, коли інформація про гідрометеорологічні умови у басейні річки обмежена або відсутня, для довгострокового прогнозування шарів стоку весняного водопілля річок використовують методи, які засновані на дослідженні часових рядів, за умови, що витрата води у замикальному створі є надійною характеристикою стану водозбору річки [14-17]. Регресійні моделі, в яких

сезонний стік прогнозується у залежності від попередніх гідрологічних та кліматичних змінних, можна розглядати як особливий випадок методу аналізу часових рядів [18-20].

Виділення невирішених раніше частин загальної проблеми. Довгострокове прогнозування шару стоку весняного водопілля р. Десни є важливим з огляду на те, що р. Десна формує боковий приплив до Канівського водосховища, яке у свою чергу використовується для виробітку електроенергії на Канівській ГЕС, питного та технічного водопостачання, регулювання стоку каскаду Дніпровських водосховищ, зрошення, рибальства та рекреаційних потреб [21, 22]. Річка Десна є транскордонною річкою (рис. 1). На території України розташовано 46 % її водозбірної території, а решта – на території російської федерації. Довгострокове прогнозування водного стоку р. Десна за методичними підходами, які розроблено у працях [1, 4, 5] виконується у відділі гідрологічних прогнозів Українського гідрометеорологічного центру ДСНС України (далі – УкрГМЦ). Станом на сьогодні застосування цих методик в оперативній діяльності УкрГМЦ, їхнє оновлення та вдосконалення неможливе через відсутність обміну гідрометеорологічною інформацією між Україною та російською федерацію, що пов'язано з російсько-українською війною.

Метою дослідження є розроблення методики довгострокового прогнозування шарів стоку весняного водопілля р. Десна – с. Літки на основі фізико-статистичного методу.

Матеріали та методи дослідження. Річка Десна починається з боліт, розташованих поблизу м. Єльня, Смоленської області, російської федерації, на висоті 238 м над рівнем моря та впадає у річку Дніпро біля Києва на висоті 92 м над рівнем моря (рис. 1) [23]. Загальна площа водозбору р. Десни становить 88900 км^2, а довжина – 1126 км.

Клімат у басейні Десни помірно-континентальний. Найхолоднішим місяцем року є січень, а найтеплішим – липень. Середня річна кількість опадів, зокрема, за даними спостережень метеорологічної станції Брянськ, становить 570-620 мм, які випадають, переважно, у теплу пору року (69% від річної кількості) [24].

Річка Десна належить до рівнинних річок та має переважно сніго-дощове живлення. Водний режим річки характеризується щорічними весняними водопіллями різної висоти і тривалості та відносно низькою літньо-осінньою меженню [24]. Весняне водопілля на річці Десна формується переважно у верхній частині водозбору, тобто на території російської федерації, де більш суворий клімат, вища залісеність та більші запаси води у сніговому покриві. У період весняного водопілля стік річки становить до 57 % річного стоку. Зимою та восени стік складає по 13 % річного стоку, а влітку – 17 % [25].

У дослідженні використано дані спостережень (показники стоку весняного водопілля) на гідрологічних постах р. Десна – с. Літки за період 1973-2023 рр. та р. Десна – м. Чернігів за період 1884-2020 рр., які опубліковані у довідниках Центральної геофізичної обсерваторії імені Бориса Срезневського.

В оперативній діяльності УкрГМЦ найбільше застосування знайшла методика, яка розроблена у праці Пашової та ін. [4]. Саме тому для оцінювання можливості застосування у цій методиці даних реаналізу, замість даних наземних спостережень. використано їхні значення з сайту ERA5-Land, створеного Службою зміни клімату Copernicus (C3S) в Європейському центрі середньострокових прогнозів (ECMWF) [26].



Рис.1. Схема розташування басейну річки Десна /
Fig. 1. Location scheme of the Desna River basin

Для розроблення нової методики довгострокового прогнозування шарів стоку весняного водопілля р. Десни використані значення телеконнекційних індексів та паттернів, які наведені на сайті Національного управління океанічних і атмосферних досліджень США (NOAA USA) [27]. Оцінювання якості розробленої методики виконано згідно до вимог діючого керівного документу [28].

У дослідженні застосовані методи кореляційного та регресійного аналізу, які дозволили знайти прогностичну залежність, а також статистичні та експертні методи аналізу, порівняння та узагальнення інформації.

Результати і їхнє обговорення

Недоступність сучасних даних гідрометеорологічних спостережень на частині водозбору р. Десна, яка розташована на території російської федерації, не дозволяє застосувати рівняння водного балансу для розроблення методики прогнозування шарів стоку весняного водопілля для гідрологічного поста р. Десна – с. Літки. Спроби оцінити запаси води у сніговому покриві та глибину промерзання ґрунту на російській частині водозбору річки Десни за даними реаналізу виявилися невдалими. Дані реаналізу про температуру ґрунту на різних глибинах виявилися малоінформативними, а дані про запаси води у сніговому покриві (водний еквівалент) – сумнівними. Зокрема, порівняння значень максимальних запасів води у сніговому покриві водозбору р. Десна – м. Чернігів за період 1960-1990 рр., визначених за даними гідрометеорологічних спостережень у методиці Пашової та ін. [4] та за даними реаналізу показує значні розходження в окремі роки та систематичне завищення значень реаналізу (рис. 2).

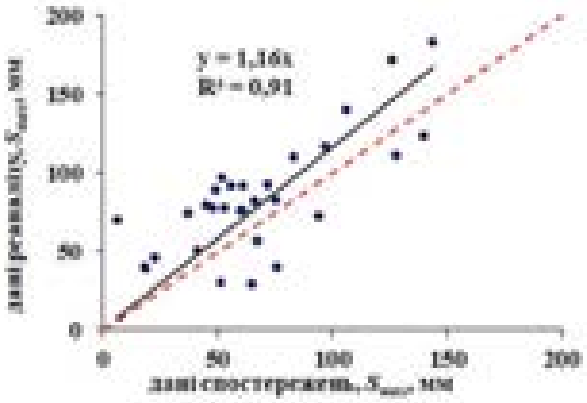


Рис. 2. Порівняння максимальних запасів води у сніговому покриві, які визначені за даними спостережень та за даними реаналізу на водозборі р. Десна – Чернігів, 1960–1990 рр.
Fig. 2. Comparison of maximum water equivalent of snow cover, determined according to observational data and reanalysis data in the Desna River – Chernihiv city catchment, 1960–1990

Окрім того, шари стоку весняного водопілля значно краще корелюють з максимальними запасами води у сніговому покриві на водозборі р. Десна - Чернігів, які визначені за даними спостережень (рис. 3а) ніж з тими ж запасами, які визначені за даними реаналізу (рис. 3б).

Враховуючи відсутність необхідної гідрометеорологічної інформації, методика довгострокового прогнозування шарів стоку весняного водопілля р. Десна – с. Літки була розроблена на основі фізико-статистичного методу. В якості предикторів для прогнозування шарів стоку весняного водопілля р. Десна – с. Літки були вибрані максимальний запас води у сніговому покриві (водний еквівалент) на водозборі за даними реаналізу, мінімальна витрата води у лютому місяці (з 1 по 21 лютого) та середнє місячне значення телеконнекційного паттерну poleur у серпні місяці (*poleur 8*) з сайту NOAA USA [27]. Цей паттерн був вибраний з 35 інших паттернів та індексів. Телеконнекційний паттерн *poleur 8* визначається характером атмосферної циркуляції над полярним регіоном та північною частиною Монголії та Китаю. Середні місячні значення телеконнекційного паттерну за серпень (*poleur 8*) найкраще корелюють з шарами стоку весняного водопілля р. Десна – с. Літки за період 1973-2020 рр. у порівнянні з іншими телеконнекційними індексами та паттернами.

Максимальний запас води у сніговому покриві (водний еквівалент) на водозборі характеризує прибуткову частину водного балансу, мінімальна витрата води у лютому місяці (з 1 по 21 лютого) дає уявлення про зволоженість ґрунтів водозбору і, відповідно, потенційні втрати стоку на інфільтрацію, а середнє

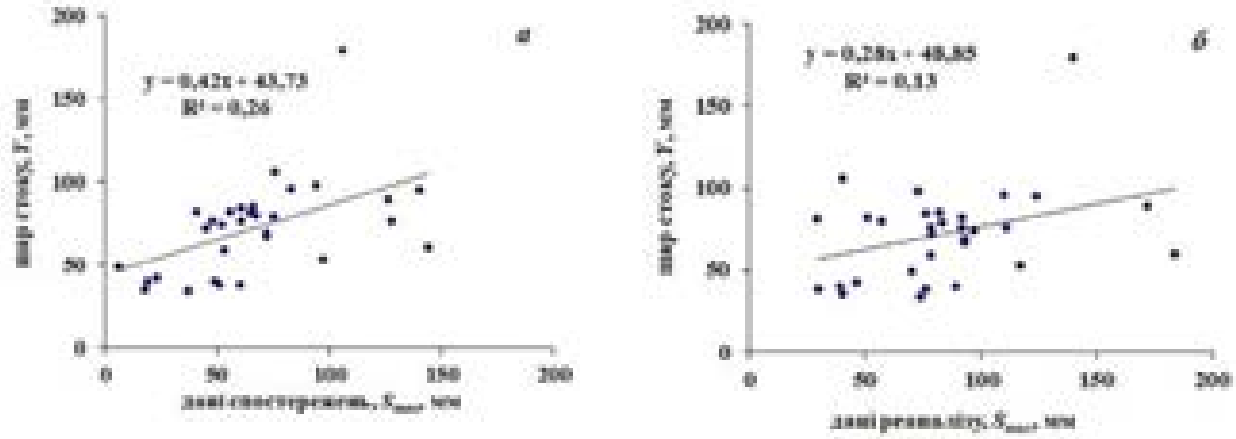


Рис. 3. *Залежності між* шарами стоку весняного водопілля *та максимальними запасами води у сніговому покриві* на водозборі р. Десна – Чернігів, які визначені за даними спостережень (а) та за даними реаналізу (б), 1960-1990 рр. /
Fig. 3. *Dependencies between the runoff depth of spring flood and the maximum water equivalent of snow cover in the Desna River – Chernihiv city catchment, determined according to observation data (a) and reanalysis data (b), 1960-1990*

Таблиця 1 / Table 1

Кореляційна матриця предикторів для прогнозування шарів стоку весняного водопілля р. Десна – с. Літки, 1973-2020 рр. / Correlation matrix of predictors for forecasting of runoff depth of spring flood of the Desna River – Litky village, 1973-2020

	Y	Smax	Qmin	poleur 8
Y	1,00			
Smax	0,25	1,00		
Qmin	0,40	-0,06	1,00	
poleur 8	-0,55	-0,34	-0,15	1,00

місячне значення телеконнекційного паттерну *poleur* у серпні місяці характеризує синоптичні процеси, які, за нашим припущенням, визначають надходження вологи на водозбір річки у зимово-весняний період.

Після побудови кореляційної матриці було виявлено відсутність статистично значимої кореляції між шарами стоку весняного водопілля та максимальними запасами води у сніговому покриві за даними реаналізу (табл. 1). Разом з цим, максимальні запаси води у сніговому покриві корелюють з телеконнекційним паттерном *poleur 8*. Отже, у прогностичне регресійне рівняння (2) увійшли тільки два предиктори: мінімальна витрата води (Q_{min}) перед початком водопілля (1-21 лютого) та середнє місячне значення телеконнекційного паттерну у серпні місяці (*poleur 8*):

$$Y = 0{,}081 \cdot Q_{min} - 10{,}814 \cdot poleur\ 8 + 42{,}72 \quad (2)$$

Випуск прогнозу шару стоку весняного водопілля на гідрологічному посту р. Десна – с. Літки за рівнянням (2) можливий не раніше 21 лютого, оскільки одним з предикторів є мінімальна витрата води, яка визначається за період 01-21 лютого. Допустима похибка перевірочних прогнозів, визначена за даними спостережень за шарами весняного стоку р. Десна – с. Літки за період 1973 – 2020 років, становить 15 мм. Статистична перевірка прогностичної залежності (2) за залежними даними показала, що у 33 випадках із 48 похибка прогнозування не перевищує допустиму похибку (15 мм). Отже, ймовірність неперевищення допустимої похибки становить 69 %, що відповідає оцінці якості методики «задовільно» згідно [28]. Відношення середньої квадратичної похибки перевірочних прогнозів ($\overline{S}$) до середнього квадратичного відхилення прогнозної величини ($\overline{\sigma}$), тобто $\overline{S}/\overline{\sigma}$, склало 0,77.

Слід зазначити, що у період 1973-2020 рр. на річці Десна не було значних весняних водопіль. Найбільший шар стоку весняного водопілля спостерігався у 1998 році та становив 105 мм. За даними спостережень р. Десна – м. Чернігів, де спостереження розпочалися у 1884 році, найбільший шар стоку весняного водопілля був у 1931 році та становив 175 мм. Також значні шари стоку весняного водопілля були відмічені у 1970 (174 мм), 1942 (165 мм), 1895 та 1917 (164 мм) і 1908 (153 мм) роках. Зважаючи на короткий ряд спостережень за параметрами весняного водопілля р. Десна – с. Літки, цей ряд був подовжений на основі кореляційного зв'язку з рядами шарів стоку р. Десна – м. Чернігів за спільний період спостережень 1973-2020 років (рис. 4). Допустима похибка прогнозування шару стоку весняного водопілля р. Десна – с. Літки, визначена за подовженим рядом, становить 21 мм. Збільшення допустимої похибки покращує оцінку якості методики з «задовільної» до «доброї», оскільки ймовірність неперевищення допустимої похибки зростає з 69 % до 85 %.

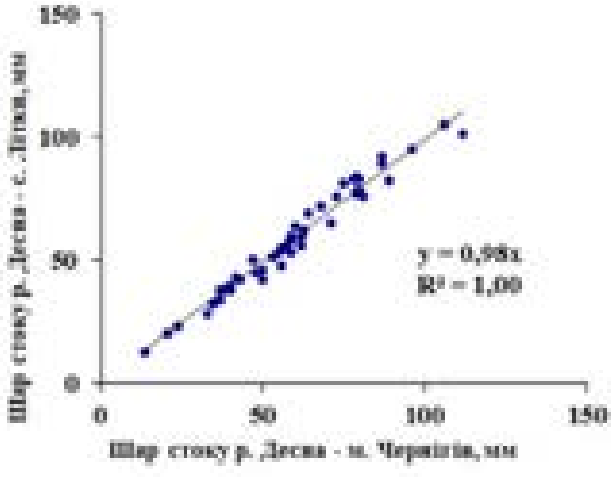


Рис. 4. *Залежність між* шарами стоку весняного водопілля *р. Десна – м.* Чернігів *та* р. Десна – *с. Літки,* 1973-2020 рр.
Fig. 4. Dependence between the runoff depths of spring flood on the Desna River – Chernihiv city and the Desna River – Litky village water gauges, 1973-2020

Використаний у роботі фізико-статистичний підхід дозволив розробити методику довгострокового прогнозування шарів стоку весняного водопілля р. Десна, в якій використовується тільки два предиктора, значення яких доступні на момент випуску прогнозу. Отриманий результат є важливим в умовах недоступності гідрометеорологічної інформації зі стокоформуючої частини басейну р. Десна. Отже, розроблена методика

може використовуватися в оперативному прогнозуванні шарів стоку весняного водопілля р. Десна в УкрГМЦ.

Зазначимо, що у світі, незважаючи на розвиток детерміністичного моделювання водного стоку річок, регресійні залежності відіграють суттєву роль у гідрологічному прогнозуванні. Так, наприклад, у праці [29] показано, що прогнозування характеристик стоку річок за ансамблем регресійних залежностей дало кращий результат у порівнянні з двома концептуальними гідрологічними моделями для 605 водозборів Австралії. У праці [30] за даними 1885 водозборів, які розташовані по всьому світу, розроблена глобальна регресійна модель для оцінювання середньорічного стоку води річок, яка показала кращій результат у порівнянні з глобальною гідрологічною моделлю PCR-GLOBWB.

Висновки

Водний стік річки Десни є основною складовою бокового припливу до Канівського водосховища. Зважаючи на недоступність даних сучасних наземних гідрометеорологічних спостережень на російській частині території водозбору річки Десни, а також на неможливість заміни цих даних даними реаналізу, нами розроблено методику довгострокового прогнозування шарів стоку весняного водопілля р. Десна – с. Літки на основі фізико-статистичного методу. До складу прогнозного регресійного рівняння увійшли два предиктори: мінімальна витрата води у першій та другій декаді лютого та середнє місячне значення телеконнекційного паттерну *poleur* у серпні місяці. Якщо перший предиктор характеризує зволоженість ґрунтів водозбору річки і, відповідно, втрати на інфільтрацію, то другий – синоптичні процеси, які, за нашим припущенням, визначають надходження вологи на водозбір річки у зимово-весняний період. Статистична перевірка методики за залежними даними показала, що при допустимій похибці 15 мм, яка визначена за період 1973-2020 роки, якість методики відповідає оцінці «задовільно», а при допустимій похибці 21 мм, яка визначена за період 1884-2020 роки, – оцінці «добре». Наступним кроком дослідження може бути оцінка якості методики за незалежними даними.

Дане дослідження виконано згідно держбюджетної теми 2/24 «Удосконалення методу довгострокового прогнозу припливу води річки Десни до Канівського водосховища в сучасних кліматичних умовах» Українського гідрометеорологічного інституту ДСНС України та НАН України (№ державної реєстрації 0124U000781).

This research was carried out according to the state budget topic 2/24 "Improving the method of long-term forecasting of water inflow of the Desna River to the Kaniv Reservoir in modern climatic conditions" of the Ukrainian Hydrometeorological Institute of the State Emergency Service of Ukraine and the National Academy of Sciences of Ukraine (state registration number 0124U000781).

Внесок авторів: всі автори зробили рівний внесок у цю роботу
Конфлікт інтересів: автори повідомляють про відсутність конфлікту інтересів
Декларація про використання генеративного штучного інтелекту: автори підтверджують, що під час підготовки рукопису не використовувалися інструменти штучного інтелекту.

Authors Contribution: All authors have contributed equally to this work
Conflict of Interest: The authors declare no conflict of interest
Declaration of use of generative artificial intelligence: The authors confirm that no AI tools were used during the preparation of the manuscript.

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Long-term forecasting of spring flood runoff depths of the Desna River

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ABSTRACT

Formulation of the problem. Long-term forecasting of the Desna River spring flood runoff depth is important given that the Desna River forms a tributary inflow to the Kaniv Reservoir. At the same time, the use of previously developed methods for such forecasting, their updating and improvement is impossible due to the lack of exchange of hydrometeorological information between Ukraine and the russian federation, which is associated with the Russian-Ukrainian war.

The objective of this paper is to develop a method for long-term forecasting of the runoff depth of the spring flood of the Desna River near the village of Litky based on the physical-statistical method.

Materials and methods. The research used observation data (indicators of spring flood) at water gauges of the Desna River – Litky village for the period 1973-2023 and the Desna River – Chernihiv city for the period 1884-2020, which are published in the directories of the Central Geophysical Observatory named after Boris Sreznevsky. In the operational forecasting of the Ukrainian Hydrometeorological Center the method of Pashova et al. (1988) as the main is used. To assess the possibility of using in it the reanalysis data their values from the ERA5-Land site, created by the Copernicus Climate Change Service (C3S) at the European Centre for Medium-Range Weather Forecasts (ECMWF), were used. To develop a new method for long-term forecasting of the Desna River spring flood runoff depth, the values of teleconnection indices and patterns were used from the website of the National Oceanic and Atmospheric Administration of the USA (NOAA USA).

ARTICLE INFO

Manuscript received
30 March 2026

Revised manuscript received
5 May 2026

Manuscript accepted
25 May 2026

Available online
30 May 2026

Results. Developed a new method for long-term forecasting of spring flood runoff depth of the Desna River near the village of Litky based on the physical-statistical method. The regression forecast equation has two predictors: the minimum discharge in the first and second decade of February and the average monthly value of the poleur teleconnection pattern in August. The first predictor characterizes the moisture content of the river catchment soils and, accordingly, infiltration losses, and the second predictor - synoptic processes that determine of moisture into the river catchment in the winter-spring period. The forecasting method has a quality rating of "satisfactory" with an acceptance error of 15 mm, determined for the period 1973-2020. The probability of not exceeding the acceptance error is 69 %, and the ratio of the mean square error of verification forecasts ($\overline{S}$) to the standard deviation of forecast value ($\overline{\sigma}$), i.e. $\overline{S}/\overline{\sigma}$ is 0.77. After lengthen the observation series of spring flood runoff depth on the Desna River – Litky village gauge based on the Desna River – Chernihiv city gauge of observation data, the acceptance error increased to 21 mm, which improved the assessment of the quality of the method from "satisfactory" to "good".

Scientific novelty and practical significance. The new developed method for forecasting the spring flood runoff depth on the Desna River makes a certain scientific contribution to the development of long-term hydrological forecasting methods in conditions of limited hydrometeorological information. This will be used in operational forecasting by the Ukrainian Hydrometeorological Center of the State Emergency Service of Ukraine.

Keywords:

spring flood, runoff depth, teleconnection indices and patterns, water balance, physical-statistical method, long-term forecasting, Desna, methodology.

In cites:

Khrystiuk Borys, Shakirzanova Zhannetta (2026). Long-term forecasting of spring flood runoff depths of the Desna River. *Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology*, (64), 293–301. https://doi.org/10.26565/2410-7360-2026-64-22 [In Ukrainian]

https://doi.org/10.26565/2410-7360-2026-64-23

UDC 551.58:551.581.1:551.577

Atmospheric rivers as an indicator of circulation variability: between the Atlantic and the Black Sea region

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ABSTRACT

Introduction. Atmospheric rivers (ARs) are a key mechanism of water vapour transport in the mid-latitudes, shaping precipitation regimes in many coastal regions of the world. Their impact on Western Europe is well studied; however, the role of ARs in Eastern Europe and their relationship with large-scale circulation regimes remain insufficiently explored.
The purpose of the study. The aim of this study is to identify statistical relationships between the frequency of atmospheric rivers in the Atlantic–European sector and the main circulation indices, as well as to analyse the potential responses of these phenomena in Eastern Europe.
The research methodology. The methodology is based on the use of the AR Reanalysis Databases V3.0 (Guan, 2021), where the identification of atmospheric rivers was carried out following the approach of Guan & Waliser (2019), taking into account integrated water vapour transport (IVT). For the correlation analysis, the ERA-Interim–based dataset (1.5° × 1.5°) was employed; circulation indices (NAO, PE, EA/WR, SCAND) were obtained from CPC; and monthly precipitation totals were taken from the ClimUAd database (0.1° × 0.1°). These data were used to calculate correlation relationships and to construct maps.
Research results. Atmospheric rivers (ARs) in the Atlantic–European sector exhibit a distinct seasonality: their frequency peaks in winter and reaches a minimum in summer, with a pronounced impact on precipitation in Eastern Europe, particularly in the Carpathians and the Black Sea region. Statistically significant correlations between AR frequency and circulation indices (NAO, SCAND, EA/WR, PE) confirm the role of large-scale atmospheric dynamics in shaping AR trajectories.
The novelty of the developments. This study proposes to consider atmospheric rivers as manifestations of large-scale atmospheric circulation dynamics. Unlike most research that focuses on the direct AR effects in Western Europe, this work is the first to highlight the potential responses of atmospheric rivers in Eastern Europe, particularly along the northern coast of the Black Sea. For the first time, a correlation analysis between AR frequency and circulation indices (NAO, EA/WR, PE, SCAND) is conducted, along with an assessment of their influence on the region's monthly precipitation.
Practical significance. The results of this study can be applied to improve the understanding of atmospheric circulation as a driver of regional hydrometeorological anomalies. Identifying the potential impact of ARs on precipitation and cloudiness in Eastern Europe will enhance methods for long-term forecasting of the water balance and extreme weather events. This is of particular value for regions sensitive to precipitation deficits or sudden heavy rainfall, especially in the contexts of agriculture, water resource management, and risk management.

ARTICLE INFO

Manuscript received
30 September 2025

Revised manuscript received
6 November 2025

Manuscript accepted
25 May 2026

Available online
30 May 2026

Keywords:

atmospheric rivers, circulation indices, correlation analysis, moisture transport, atmospheric precipitation, seasonal variability, Eastern Europe, Atlantic-European sector, reanalysis.

In cites: Shchehlov Oleksandr, Shpyg Vitalii, Fomichev Nikita, Dudarenko Ivan (2026). Atmospheric rivers as an indicator of circulation variability: between the Atlantic and the Black Sea region. *Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology*, (64), 302–313. https://doi.org/10.26565/2410-7360-2026-64-23

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Introduction

Atmospheric rivers (ARs) are narrow corridors (tens to hundreds of kilometres wide) of intense water vapour transport that play a key role in meridional moisture exchange and act as important triggers of extreme precipitation and strong wind events in coastal regions [34]. ARs transport a substantial portion of water vapour from the tropics toward the poles in the mid-latitudes, and they are a critical component of the global water cycle and the atmospheric energy balance. Certain coastal regions–for example, Western Europe, California, Chile, and the Caucasus–exhibit strong dependence on ARs in terms of moisture regimes and precipitation patterns [15, 19, 20, 22], as well as in shaping the state of the upper ocean layers in coastal zones [32]. ARs often enhance heavy precipitation, particularly on windward mountain slopes, i.e. through the orographic effect [7]. They also influence soil moisture recharge, mountain snow accumulation, and the corresponding river runoff regime [15, 28, 35]. For instance, the study [17] emphasise that ARs are a key driver of extreme precipitation and the mass balance of the Antarctic ice sheet.

Analysis of recent research. There are several approaches to identifying ARs, which are based on the calculation of specific indicators (IVT, IWV, VIMFC). The methodology and description of the formation features of this phenomenon are provided in [8, 28, 37]. Accurate information on AR dynamics has been obtained through field observations, particularly aircraft campaigns [26, 27]. Developed AR detection algorithms have enabled researchers to generate ready-to-use AR catalogues, such as [6]. For several regions, the relationship between ARs and precipitation is well documented [2, 13, 16, 19]. Precipitation is the key manifestation of ARs during their landfall or when crossing orographic barriers. ARs account for over 90% of the horizontal water vapour transport from the tropics to the mid-latitudes [8]. The large water vapour content concentrated in ARs creates highly favourable conditions for precipitation if uplift occurs (e.g., frontal zones or mountain ranges). ARs do not directly cause precipitation but act as a moisture supplier to frontal zones (warm fronts), cyclones, and their warm conveyor belts [3]. According to [35], about 80% of AR events in their dataset were associated with extratropical cyclones. ARs can also trigger stratiform precipitation events in areas of strong convection under local instability. For example, in [5] it is concluded that future research requires higher spatial resolution data (a few kilometres) and modelling of a larger number of cases to gain a deeper understanding of these processes. It is noted that ARs may occur under favourable conditions for the concurrent development of smaller-scale convective phenomena (structures of the “AR rapids” type), which are evident in vertical cross-sections with a temporal resolution of 30 minutes and horizontal scales of 5–7 km. Given the importance of ARs in the climate system, their response to climate change is of particular interest. High internal variability driven by synoptic storms remains the main source undermining the predictability of extreme ARs [23]. It is also important to emphasise that different AR detection algorithms, data assimilation inhomogeneities, and other discrepancies among reanalyses (MERRA-2, ERA5, JRA-55) affect the results and the reliability of detected trends in AR changes and precipitation linkages, especially over land [10, 25]. Studies assessing future climate change suggest that ARs will become more frequent and intense under global warming [4, 14, 18, 24, 32, 35]. According to climate model analysis [35], future extreme ARs are generally expected to be associated with weaker storm systems, to be positioned farther from the centres of extratropical cyclones, and to develop less dependently on storm dynamics due to increased moisture supply under warmer conditions. Moreover, ARs have a more pronounced and longer-lasting impact on atmospheric moisture increases in the Arctic than the event duration itself, and this effect can be quantitatively distinguished from overall humidity changes [36]. Attempts to investigate AR impacts on more continental regions have yielded interesting results. For instance, [33] showed that ARs influence not only western coastal areas but also far inland. According to this study, under climate warming, ARs are projected to intensify and occur more frequently, with their landfall zones shifting northward, making these findings particularly relevant for precipitation forecasting and extreme-event risk assessment.

Unresolved aspects of the problem. While their role along the Western European coast is well documented (a detailed review of the issue is provided in [29]), much less attention has been given to the impact of ARs in the inland parts of the Atlantic–European sector, particularly in Eastern Europe [30]. According to available results, ARs were present in many cases of heavy precipitation in the northwestern region of the country; however, a considerable proportion of extreme precipitation events were not associated with ARs. Although the frequency of ARs in Eastern Europe, and specifically in the Black Sea region, is not as high as on the Western European coast, the Eastern Mediterranean and the Black Sea themselves act as substantial moisture sources, partly offsetting the general decline in AR occurrence with distance from the ocean. The relationship between AR frequency and large-scale circulation regimes, which control the trajectories and intensity of atmospheric moisture transport, also requires further clarification. In this article, we attempt to view ARs as manifestations of

large-scale atmospheric circulation mechanisms. To this end, we analyse how the frequency of AR events is related to circulation indices in the Atlantic–European sector (NAO, PE, EA/WR, SCAND), and we also investigate whether there are any detectable responses to ARs on the periphery of this sector, in Eastern Europe–particularly in terms of monthly precipitation over Ukraine.

Purpose of the article. The aim of this study is to identify statistical relationships between the frequency of atmospheric rivers in the Atlantic–European sector and the main circulation indices (NAO, PE, EA/WR, SCAND), as well as to analyse the responses of ARs in terms of precipitation over the territory of Ukraine.

Methodology and data. To determine the frequency of atmospheric rivers, we used the AR Reanalysis Databases V3.0 [6]. The AR identification methodology [9] is based on integrated vapour transport (IVT). The IVT index accounts for both the meridional and zonal components of air and moisture transport. In the catalogue, an AR is recorded if the following conditions are met: a) IVT exceeds the 85th percentile and is not less than 100 kg m^{-1} s^{-1}; b) the orientation of the flow in the region of the specified IVT values deviates by no more than 45° from the northward direction; c) the length of the AR is at least twice its width. For this study, we used the version of the database based on the ERA-Interim reanalysis, which has a spatial resolution of 1.5° × 1.5°. In the NetCDF file structure, the variable "shape" was employed to determine the spatial coverage of ARs. Data on the circulation indices NAO, PE, EA/WR, and SCAND [1, 11], calculated by the Climate Prediction Center, were obtained from [12]. We computed Pearson correlations between circulation indices and AR frequency at each grid point on a monthly timescale. To assess the correlation between AR frequency and monthly precipitation in Ukraine, we used the ClimUAd database with a spatial resolution of 0.1° × 0.1° [21]. For visualisation, maps were generated using Python libraries.

Results

The frequency and trajectories of ARs potentially shape the seasonal and interannual structure of atmospheric moisture: changes in AR frequency or shifts in their pathways may lead to moisture redistribution across regions or to its deficit. To better understand the seasonal

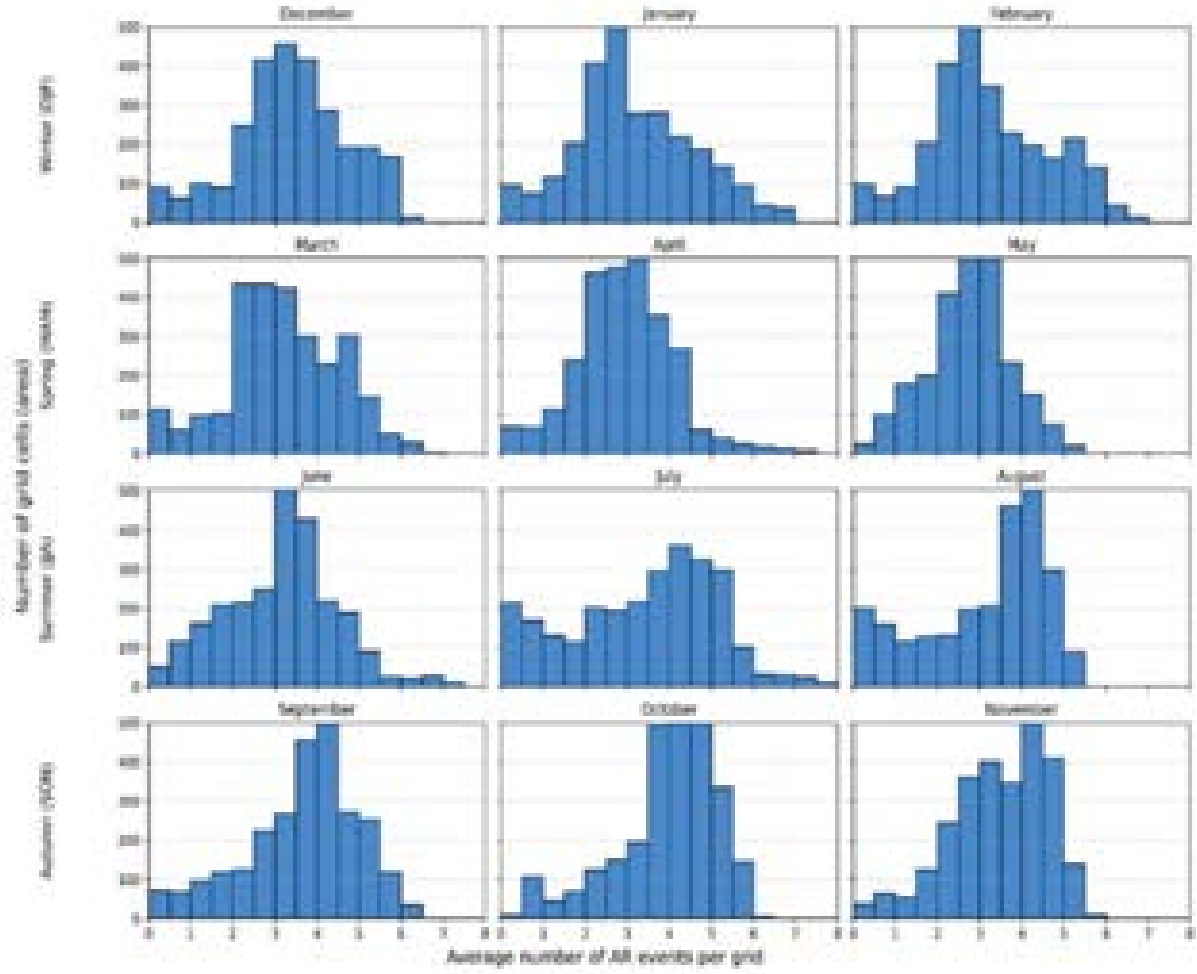


Fig. 1. Seasonal histograms of the mean monthly number of AR events per grid over the Atlantic–European sector (30–80°N, 50°W–70°E), 1990–2019

characteristics of AR occurrence in the Atlantic–European sector, we analysed the distribution of AR event frequency by month for the period 1990–2019. For this purpose, histograms were constructed to illustrate the spatial variability of AR counts at individual grid points within each month of the year. This approach makes it possible to identify not only the general seasonal trends but also the spatial heterogeneity and potential "hotspots" of AR activity throughout the year. Figure 1 presents histograms of AR event frequency in the Atlantic–European sector within 30°–80° N and 50° W–70° E, by month, for the years 1990–2019. In the histograms, the X-axis represents the mean number of AR events during a month, while the Y-axis shows the number of grid points (pixels/stations/cells) where AR events were observed within that month (corresponding to the value on the X-axis).

The winter months (December–January) are characterised by the highest number of grid with an average of 2–4 AR events per month (see Fig. 1). The distribution exhibits a long right-hand tail (up to 6–7 events), indicating the presence of individual locations with very high AR frequency (e.g., the western coast of Europe or the Atlantic sector). The winter period corresponds to the peak of westerly transport activity in Europe, which also represents the main season of AR activity in the region. It should be noted, however, that the greatest recurrence of AR events occurs over the Atlantic Ocean.

In spring (March–May), the peaks remain fairly pronounced. The same mean values of about 3–4 ARs per month dominate, but March shows a leftward shift, whereas May tends toward a right-hand tail. Compared to winter, fewer grid cells exceed 4 ARs per month.

In summer, the maximum shifts slightly to the right (4–5 events per month), with August showing the most "right-skewed" distribution, reflecting higher AR intensity in some grid cells. Despite this shift toward more frequent AR occurrence in certain areas, extensive regions record fewer than 3 ARs per month. In practice, this is explained by the much lower incidence of ARs over the southern part of the continent (including the Mediterranean) during summer, while the main activity is concentrated in the north.

In autumn, a transition is observed from a left-skewed distribution in September to more right-

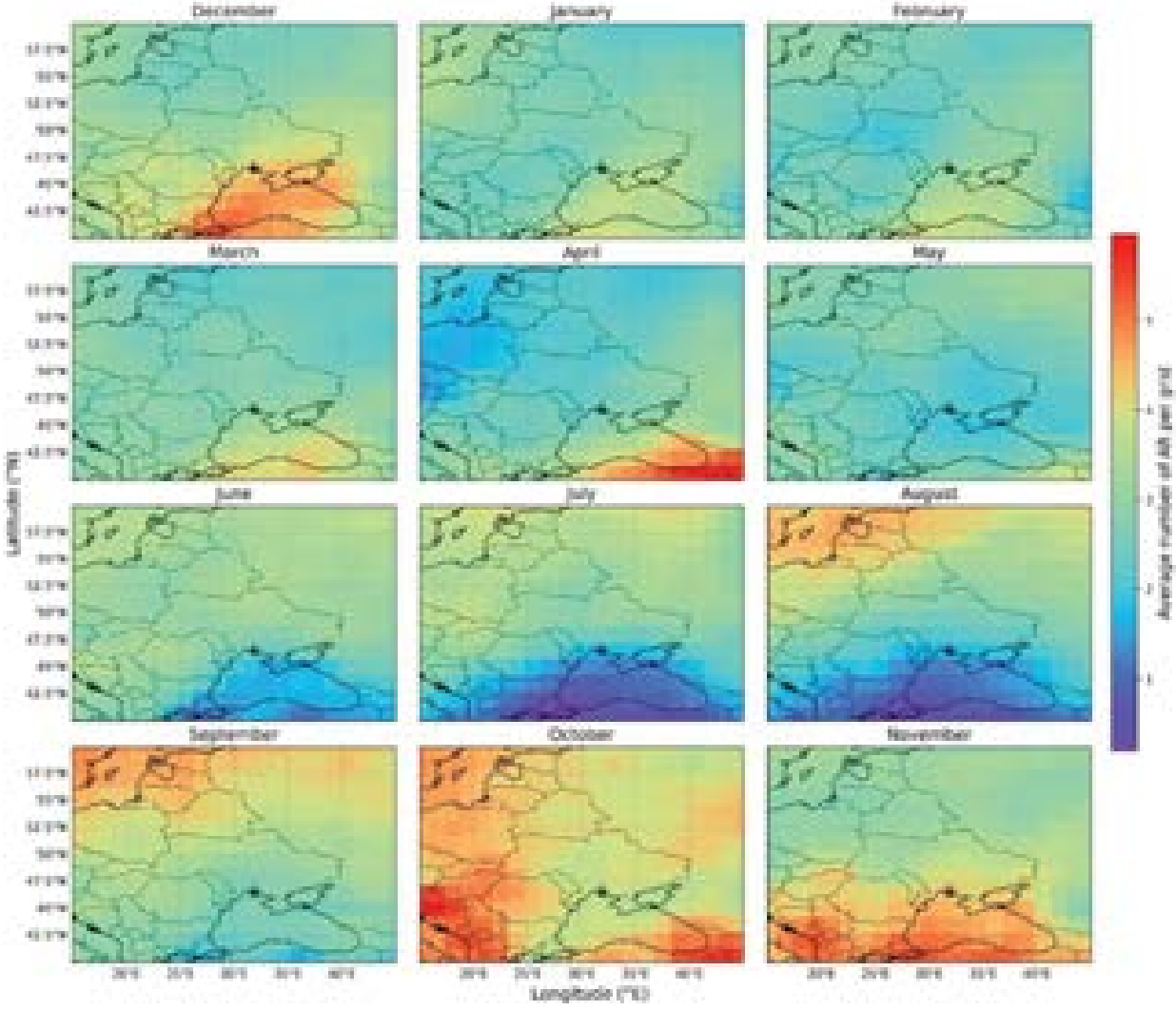


Fig. 2. Average monthly number of days with AR events in the Eastern Europe

skewed ones in October–November, indicating an increasing number of grid cells with elevated AR counts. Autumn is the period of most active AR occurrence over southwestern and central continental Europe.

Thus, atmospheric rivers in the Atlantic–European sector exhibit a clearly defined seasonality: their activity peaks in winter (December–February), while the lowest number of events is recorded in summer (July–August). Spring and autumn serve as transitional phases, with activity gradually intensifying in autumn, particularly in November. Spatial distribution is also heterogeneous: in winter, the long-tailed distribution indicates the existence of localised zones with high AR frequency.

Before examining the relationship between AR frequency in Eastern Europe, it is important to identify regional differences in AR occurrence frequency across the sector (Fig. 2). Spring–summer (April–August). During these months, a general decrease in AR frequency is observed across the entire region. The minimum values occur in June and July, when blue shades (1–3 AR days per month) dominate throughout, with the lowest frequencies in the southern areas (southern Ukraine and the Black Sea coast). In August, a north–south gradient emerges, with higher AR frequency in the north (e.g., in the Baltic countries up to 4–5 ARs per month).

Autumn–winter (September–March) is the period of highest AR frequency, with maxima over southern Ukraine and the Black Sea coast. December and October are particularly pronounced, showing maxima exceeding 4–5 ARs per month in some areas. In November, AR frequency is moderate across most of the territory, with local maxima in the south. In January and February, AR frequency gradually decreases compared to December, though the spatial pattern of maxima over the southeast remains.

Transitional months (March, September). In March, frequency is similar to January–February but somewhat more evenly distributed, with a decline in the north. In September, a transition toward the autumn maximum is observed, with increasing AR frequency over central and southern Ukraine.

In summary, the southern part (Black Sea region) maintains a more stable maximum during the cold

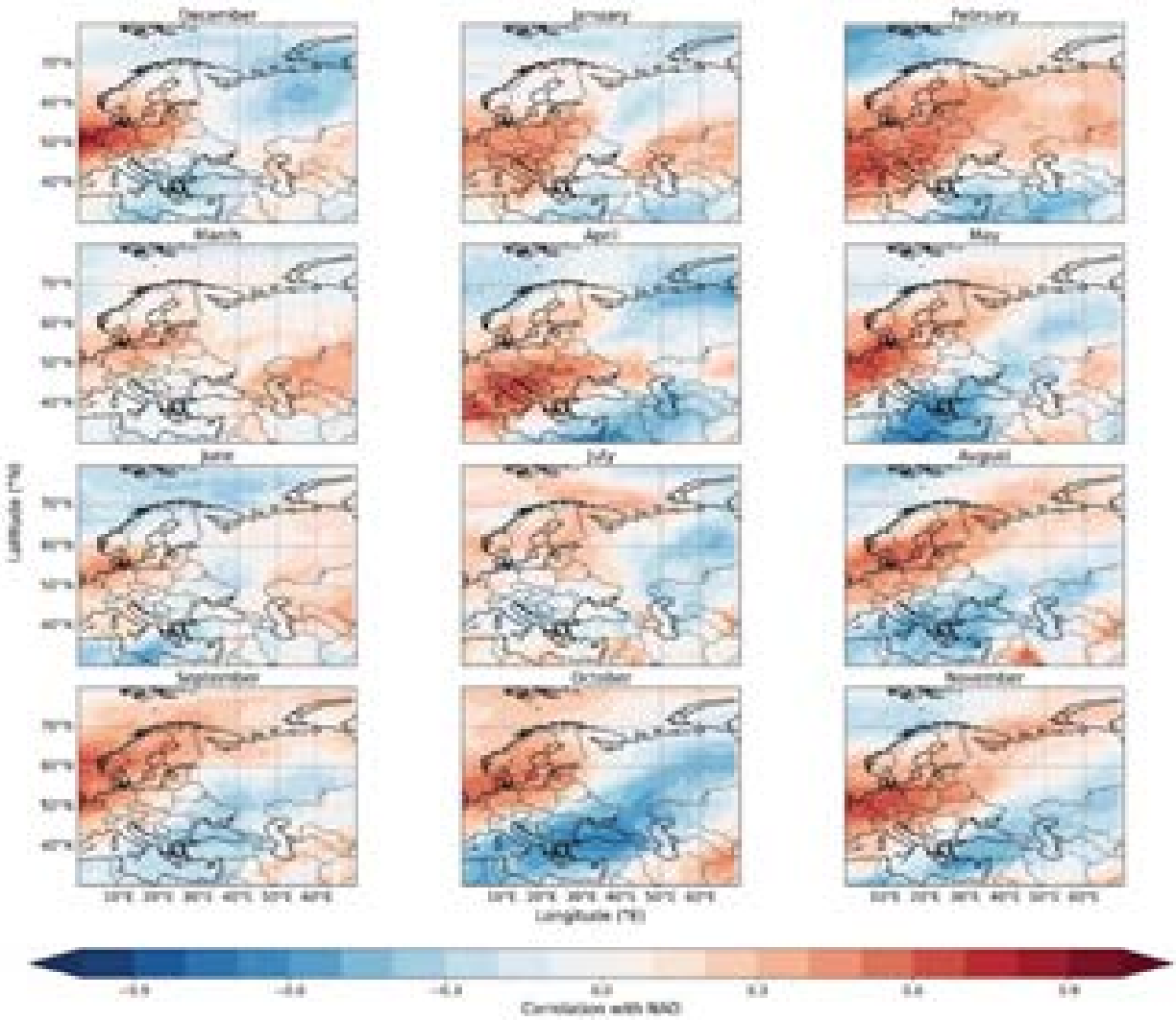


Fig. 3. Correlation maps between AR frequency at regular grid points and the NAO circulation index

season (October–March), likely reflecting the active role of Mediterranean and Black Sea cyclones in moisture transport. The northern areas (Belarus, northern Ukraine) show minimal AR frequency throughout the year, except for isolated increases in August and September.

Thus, AR seasonality in Eastern Europe is well defined: maxima occur in autumn and early winter (October–December), while minima are observed in summer (June–July). Spatial features of AR frequency indicate a dominance of AR activity in the southern part of the region, especially during the cold season, and a reduced role in the north. This pattern corresponds well with the seasonal activity of Mediterranean cyclones and the overall configuration of the westerlies that form ARs in winter.

Figure 3 shows correlation maps of AR frequency at grid points with the NAO index.

Given the pronounced seasonality of atmospheric rivers (ARs) in Eastern Europe, it is appropriate to investigate the extent to which changes in their frequency are linked to variations in large-scale circulation processes. Atmospheric circulation indices, such as the North Atlantic Oscillation (NAO), strongly influence the position and intensity of the westerlies, which in turn are a key mechanism for AR formation. Therefore, the subsequent analysis focuses on the spatio-temporal correlation structure between monthly AR frequency and NAO values in order to identify potential dynamical linkages between these phenomena. As shown in Fig. 3, the spatial structure of the correlation response changes substantially throughout the year. A notable feature is the significant positive relationship between NAO and AR frequency over northwestern Europe during almost the entire year, with the exception of a few months (March, June, and July, when the coefficients are somewhat reduced). A second fairly persistent zone of negative correlation is observed over the eastern Mediterranean, the Balkans, Turkey, and the Black Sea region. The maps of monthly correlations between AR frequency and the NAO index clearly reveal a structure of alternating zones of positive and negative correlations oriented roughly southwest–northeast (SW–NE). This structure migrates throughout the year, changing its position and spatial extent, with the connection

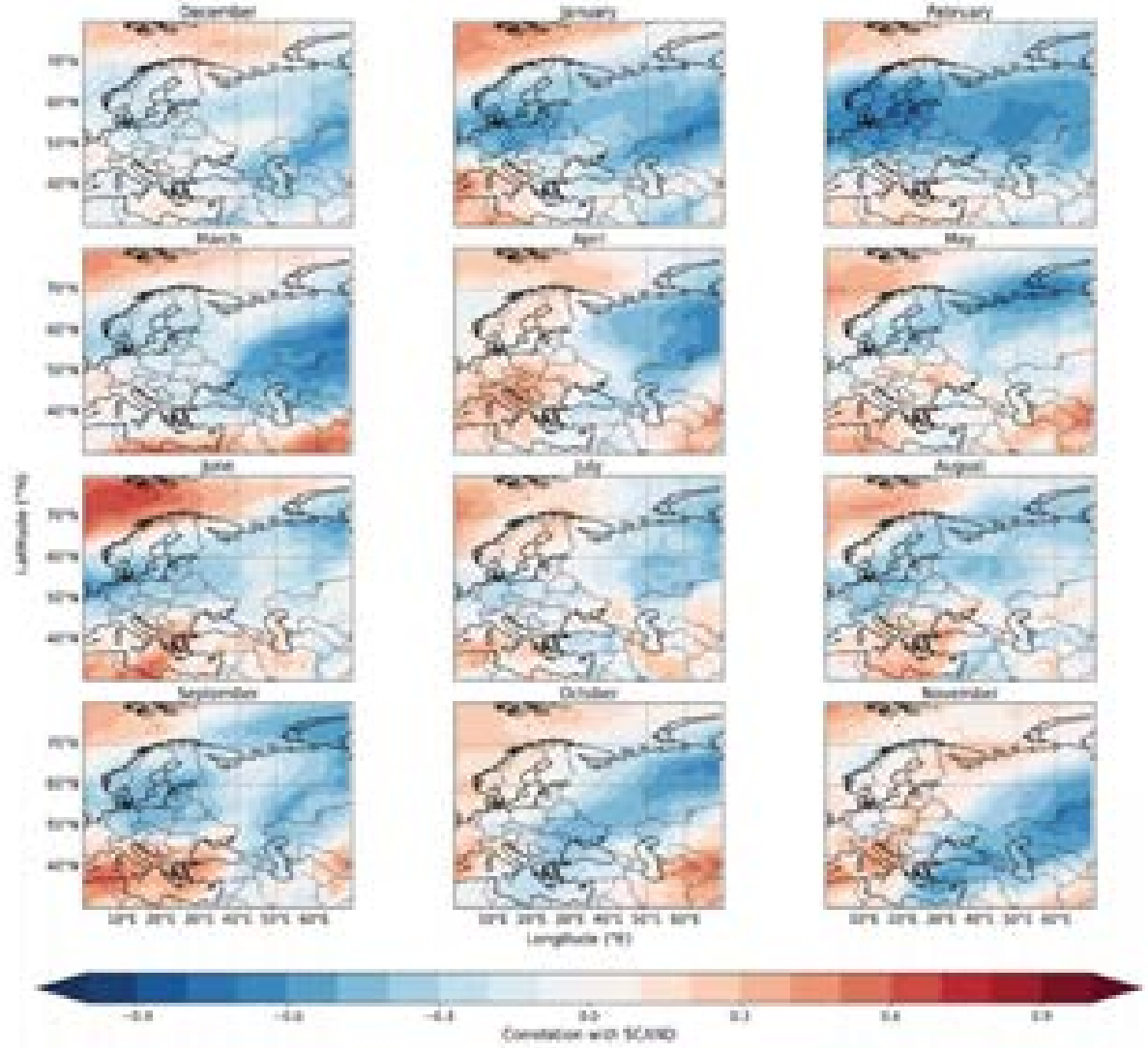


Fig. 4. Correlation maps between AR frequency at regular grid points and the SCAND circulation index

to ARs being stronger in some months (e.g., the autumn–winter period) and weaker in others (June–July). Overall, it reflects the long-term seasonal shifts in the climatic position of the jet stream, AR trajectories, and the influence of NAO.

In addition to NAO, other mid-latitude circulation patterns play an important role in shaping regional atmospheric conditions in Eastern Europe. One of these is the SCAND index (Scandinavian pattern), consisting of a primary circulation centre over Scandinavia and weaker centres of opposite sign over western Europe and eastern Russia/western Mongolia. The circulation state in these centres determines the position of zonal/meridional air transport in the region and can block or redirect cyclone pathways–thus potentially influencing AR occurrence.

Fig. 4 presents correlation maps between AR frequency at grid points and the SCAND index. A characteristic feature of the correlation between AR frequency and the SCAND index is that positive coefficients are mostly concentrated over oceanic areas, while negative ones dominate over the continental part of Europe. In the context of Eastern Europe, a certain negative response is observed in the northern part of the region during specific months–January, February, June, and August–October. The southern parts of the region show negative correlations in October and November. In the remaining months, as well as in parts of the aforementioned periods, an extensive zone of negative correlation is evident to the east of Europe.

The Polar/Eurasia (PE) index, which is associated with variations in upper-level pressure over northern Eurasia, reflects shifts in the configuration of the Arctic front, which in turn may affect the pathways and frequency of atmospheric rivers. Although a certain pattern of alternating positive and negative correlations between PE and AR frequency can be observed, the correlation coefficients do not indicate a statistically significant relationship, particularly for Eastern Europe. Therefore, these maps are not included in the article.

The East Atlantic/Western Russia (EA/WR) index, which characterises wave-like oscillations extending from the Atlantic to western Siberia, can influence thermal contrasts and the stationarity of cyclonic activity, thereby determining favourable or unfavourable conditions for AR formation during transitional seasons. The monthly correlation between this index and AR frequency is shown in Fig. 5.

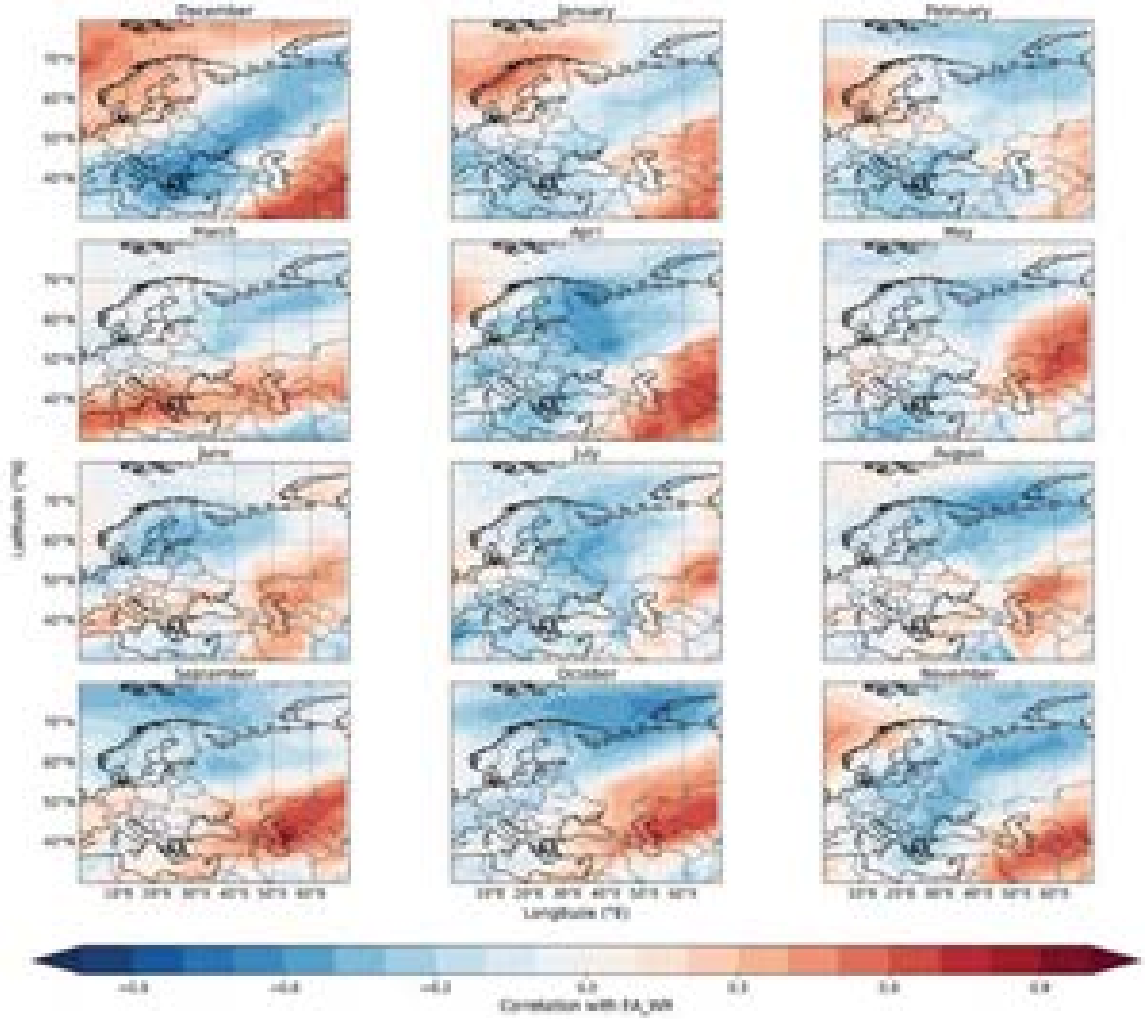


Fig. 5. Correlation maps between AR frequency at regular grid points and the EA/WR circulation index

The correlation maps between AR frequency and the EA/WR index exhibit a distinctive feature: alternating elongated zones of positive and negative correlations, oriented southwestward or zonally extended, with their positions shifting somewhat from month to month. This pattern can be explained by the seasonal reorganisation of mid-latitude circulation, particularly the displacement of major jet streams and atmospheric action centres (patterns). For Eastern Europe–primarily for Ukraine–the period from November to February shows the clearest signal, with a significant negative correlation between the EA/WR index and AR frequency. Over the broader domain, the zones of positive correlation are generally displaced either eastward or southward of Eastern Europe.

Finally, the article presents correlation maps between monthly precipitation totals from ClimUAd [21] and AR frequency (Fig. 6). As shown in Fig. 6, for the period from October to April a strong positive correlation is evident across most of Ukraine, particularly in the west and north. This indicates that an increase in AR frequency is accompanied by higher precipitation in these regions, with the strongest link observed in the Carpathians. In summer (June–August), negative correlations (down to –0.5) are observed in the south and southeast, meaning that in years with higher AR frequency, these areas experience less precipitation. This may suggest that summer ARs do not reach this part of Ukraine, likely due to the blocking effect of the Carpathian Mountains as an orographic barrier, as well as the greater role of local convective processes during the summer season.

Thus, western and northern Ukraine are the most sensitive to the influence of ARs, especially in the cold season. Southern regions of Ukraine show an inverse relationship in summer, probably due to locally driven convective precipitation that is independent of ARs, combined with the orientation of the Carpathians along the pathways of moist airflows.

It is also noteworthy that there is a cyclic pattern, with ARs exerting the strongest influence in winter, a weakening of this effect in summer, and a renewed increase in autumn. Therefore, although extreme precipitation events are not always necessarily linked to ARs [30], from a climatic perspective, on monthly or longer timescales, precipitation anomalies correlate well with AR frequency over Ukraine.

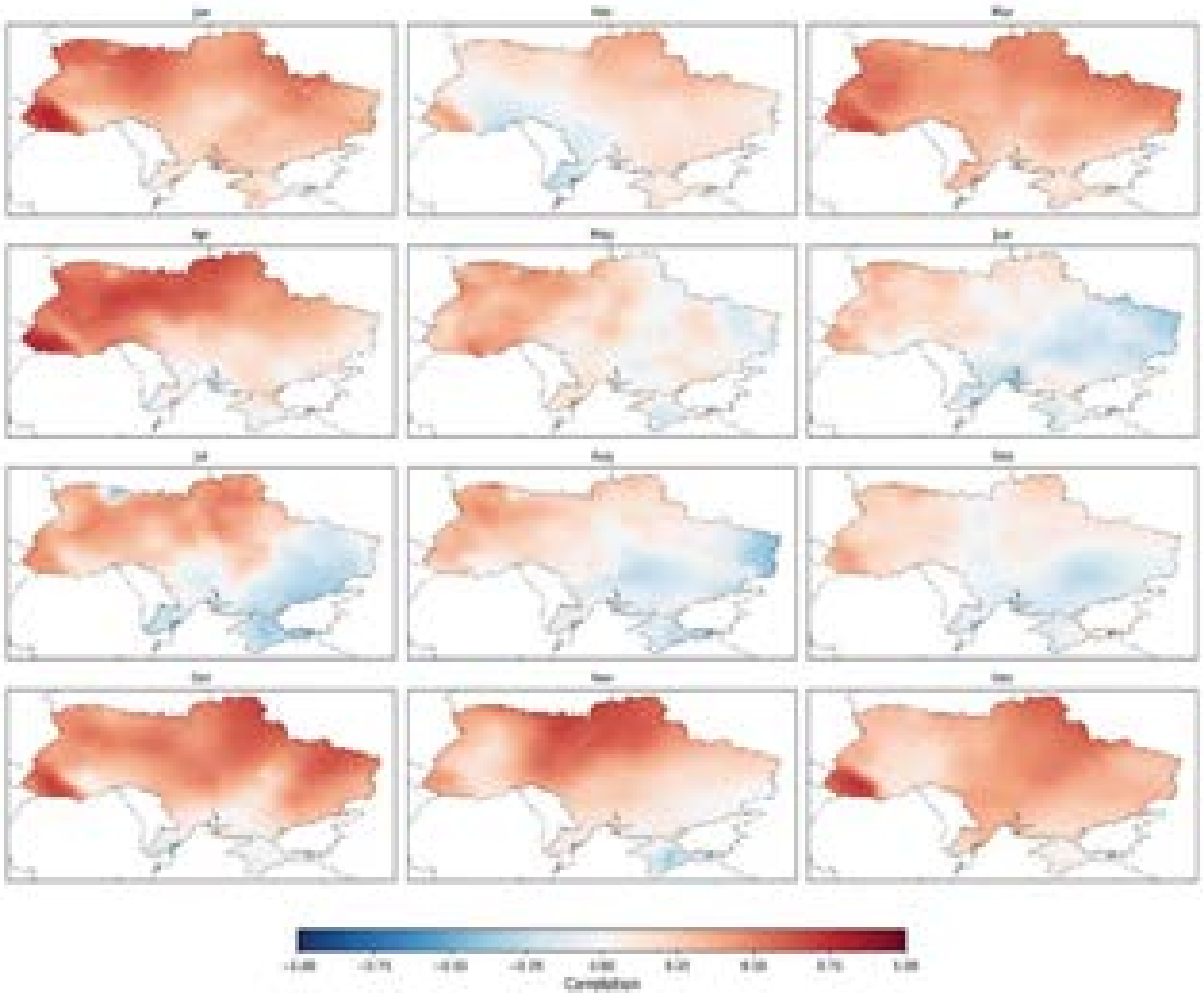


Fig. 6. Correlation between AR frequency in the region (20–45° E, 42–60° N) and monthly precipitation totals (based on ClimUAd data)

Conclusions

Thus, the maximum AR activity in the Atlantic–European sector occurs in winter (December–February), when westerly transport is most intense. The minimum activity is observed in summer (June–July), when most of the region is under anticyclonic control. Spring and autumn act as transitional periods, with November showing a sharp increase in AR frequency. In Eastern Europe (particularly the Black Sea region), AR activity also peaks in the cold season, while summer is characterised by a minimum number of events.

In Western Europe, ARs are most frequent, corresponding to landfall from the Atlantic. In Eastern Europe, their role is less pronounced, but local maxima are detected along the Black Sea coast and in the southern regions of Ukraine, especially in autumn and winter. In the northern part of the region (Belarus, northern Ukraine), ARs are less significant, except during the transitional months (August–September).

In this study, we assessed the correlation between monthly AR frequency and monthly values of atmospheric circulation indices. For NAO, a stable positive correlation with ARs is observed in northwestern Europe and a negative correlation in the Eastern Mediterranean and the Black Sea region, reflecting the control of the jet stream over AR trajectories. For SCAND, predominantly negative correlations over continental Europe highlight the blocking role of the Scandinavian pattern. For EA/WR, the strongest negative relationship in Eastern Europe is observed in winter (November–February). For PE, the relationships are weaker but indicate a potential influence of Arctic front displacements on AR trajectories.

During autumn and winter, increased AR frequency is strongly associated with positive precipitation anomalies in western and northern Ukraine, particularly in the Carpathian Mountains. In summer, however, southern and eastern Ukraine show an inverse relationship (more frequent ARs correspond to less precipitation), which can be explained by the predominance of local convective rainfall.

The results of this study can be used to improve physico-statistical long-term forecasting of extreme events (heavy rainfall, droughts) in Eastern Europe. The increase in AR frequency is also expected to coincide with greater cloud cover and reduced solar radiation, indicating that ARs may affect the regional radiation balance. Identifying the influence of ARs on humidity and precipitation has practical value for agriculture, water resource management, and risk management in the Eastern European region.

Внесок авторів: всі автори зробили рівний внесок у цю роботу
Конфлікт інтересів: автори повідомляють про відсутність конфлікту інтересів
Декларація про використання генеративного штучного інтелекту: автори підтверджують, що під час підготовки рукопису не використовувалися інструменти штучного інтелекту.

Authors Contribution: All authors have contributed equally to this work
Conflict of Interest: The authors declare no conflict of interest
Declaration of use of generative artificial intelligence: The authors confirm that no AI tools were used during the preparation of the manuscript.

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ISSN 2410-7360 (Print)
ISSN 2411-3913 (Online)
Вісник Харківського національного університету імені В.Н. Каразіна Серія «Геологія. Географія. Екологія» 2026 64 С. 302–313
Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology 2026 64 302–313

Атмосферні річки як індикатор мінливості циркуляції: між Атлантикою та Чорноморським регіоном

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АНОТАЦІЯ

Метою статті є виявлення статистичних зв'язків між частотою атмосферних річок в Атлантико-Європейському секторі та основними індексами циркуляції, а також аналіз потенційних відгуків цих явищ у Східній Європі. Методологія дослідження базується на використанні каталогу атмосферних річок (Guan, 2021), де ідентифікацію атмосферних річок здійснено за підходом Б. Гуана та Д. Валайзера (Guan & Waliser, 2019) з урахуванням інтегрального перенесення водяної пари (IVT) на основі даних реаналізу ERA-Interim. Для кореляційного аналізу використано індекси циркуляції NAO, PE, EA/WR, SCAND, а також місячні суми опадів із бази даних ClimUAd. Встановлено, що атмосферні річки в Атлантико-Європейському секторі характеризуються чіткою сезонністю з найвищою частотою їхньої появи взимку та мінімумом влітку. Виявлено просторово неоднорідні зв'язки між повторюваністю АР та основними типами великомасштабної атмосферної циркуляції. Для індексу NAO додатна кореляція з повторюваністю АР спостерігається в Північно-Західній Європі, а від'ємна – у Східному Середземномор'ї та регіоні Чорного моря, що може бути пов'язано зі змінами положення та інтенсивності струминних течій і їхнім впливом на траєкторії АР. Для індексу SCAND переважно від'ємні значення коефіцієнта кореляції над континентальною Європою можуть свідчити про вплив блокуючих процесів на повторюваність і траєкторії АР. Для індексу EA/WR найбільший обернений зв'язок у Східній Європі спостерігається протягом періоду листопад–лютий. Для індексу PE зв'язки слабші, але вказують на потенційний вплив зміщень арктичного фронту на траєкторії АР. Статистично значущі зв'язки між частотою АР в окремих регіонах та індексами циркуляції підкреслюють роль великомасштабної динаміки атмосфери у формуванні траєкторій АР. Виявлено, що в осінньо-зимовий період збільшення кількості випадків атмосферних річок у Східній Європі тісно корелює з додатними аномаліями опадів на заході та півночі України, зокрема в Карпатах. Влітку, навпаки, на півдні та сході України спостерігається зворотна залежність (вища частота АР пов'язана з меншою кількістю опадів), що можна пояснити зміною механізму формування основної частки опадів у загальній сумі за рахунок переважання локальних конвективних процесів, що супроводжуються сильними опадами.

ІНФОРМАЦІЯ ПРО СТАТТЮ :

Рукопис надійшов
30 вересня 2025

Отримано після рецензування
6 листопада 2025

Затверджено до друку
25 травня 2026

Опубліковано онлайн
30 травня 2026

Ключові слова:

атмосферні річки, індекси циркуляції, кореляційний аналіз, перенесення вологи, атмосферні опади, сезонна мінливість, Східна Європа, Атлантико-Європейський сектор, реаналіз.

ЕКОЛОГІЯ | ECOLOGY

https://doi.org/10.26565/2410-7360-2026-64-24

UDC 556.531:556.114:504.064(477.7)

Factor-cluster profiling of water quality in the Southern Bug Basin

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ABSTRACT

Introduction. The Southern Bug River Basin is one of the largest water-management systems of Right-Bank Ukraine, where natural runoff seasonality combines with sustained pressure from urbanized areas, agriculture, municipal wastewater, and industry. Existing studies either assess isolated water-quality indices, apply multivariate statistics without regulatory interpretation, or treat Ukraine at a generalized inter-basin level, so a reproducible basin-scale profile combining multiyear averages, seasonality, regulatory exceedances, and site typology is lacking for the Southern Bug. The purpose of the study was to perform factor-cluster and regulatory-index profiling of long-term hydrochemical series for rivers of the Southern Bug Basin, identifying reaches dominated by organic, nutrient, or mineralization-salinity pollution and ranking sites by hydrochemical risk. The object is surface waters of rivers within the Southern Bug Basin; the subject is the long-term structure of hydrochemical indicators, their seasonal variability, regulatory exceedances, and cluster profiles of monitoring sites.

Methods. The analysis used processed data of the state surface-water monitoring system of the State Water Agency of Ukraine for 13 January 2003 – 18 March 2026 (5,654 records, 95 sites). After plausibility control, 57 technical extremes were removed. Multiyear mean concentrations and seasonal profiles were calculated for organic-oxygen, nutrient, and mineralization-salinity blocks. Exceedance ratios and violation frequencies were computed against domestic-use and fishery-use reference values, and a screening index I6 was built as the mean of the six highest partial exceedance ratios per site. Indicators were robustly standardized, visualized by principal component analysis, and grouped by k-means clustering.

Results. Under domestic-use reference values, the most frequent exceedances were COD (42.9% of samples), permanganate oxidizability (40.8%), and BOD5 (14.8%). Under fishery-use reference values, violations were far more widespread: BOD5 – 60.4%, COD – 42.9%, sulphates – 42.4%, permanganate oxidizability – 40.8%, nitrites – 31.5%, ammonium nitrogen – 18.8%. Seasonal profiles revealed oxygen-regime stress in summer (mean dissolved oxygen 7.60 mg/dm³ versus 10.80 mg/dm³ in winter), with higher COD and permanganate oxidizability in the warm period. PCA showed the leading components reflect nutrient enrichment and mineralization-salinity processes. Clustering of 48 sites yielded three profiles: organic-oxygen (43 sites, basin-wide background pressure),

ARTICLE INFO

Manuscript received
5 March 2026

Revised manuscript received
9 May 2026

Manuscript accepted
25 May 2026

Available online
30 May 2026

Keywords:

surface waters; Southern Bug; hydrochemical profile; state monitoring; organic pollution; nutrients; mineralization; maximum permissible concentration; clustering; pollution index.

In cites: Bezsonnyi Vitalii, Nekos Alla, Davydova Oksana, Balatska Natalia, Kramarenko Dmytro, Cherevychna Nataliia (2026). Factor-cluster profiling of water quality in the Southern Bug Basin. *Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology*, (64), 314–330. https://doi.org/10.26565/2410-7360-2026-64-24

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mineralization-salinity (3 sites), and nutrient (2 sites, upper reaches). The highest I6 values occurred near the Bug Estuary, the lower Inhul River in Mykolaiv, and the upper Southern Bug downstream of Khmelnytskyi; under fishery-use values, upper-basin sites showed a sharp risk increase, with ammonium nitrogen as the limiting factor.

Conclusions. Combining multiyear and seasonal profiling with regulatory exceedance analysis and cluster typology provides an objective, reproducible screening tool for the Southern Bug Basin. Organic-oxygen loading dominates basin-wide, nutrient enrichment forms a distinct risk pattern in the upper reaches, and mineralization-salinity pollution is spatially localized. The identified priority sites give a scientific basis for optimizing the monitoring network and planning water-protection measures, without substituting for official ecological-status classification.

Introduction

The Southern Bug Basin is a water-management system in which natural seasonality of runoff is combined with anthropogenic pressure from urbanized areas, agricultural landscapes, municipal infrastructure, and recreational use of water resources. For such basins, ecological interpretation of long-term hydrochemical series cannot be limited to describing mean concentrations alone: it requires a combination of regulatory assessment, seasonal profiling, identification of priority indicators, and grouping of monitoring sites according to similarity of hydrochemical conditions. This framework is especially relevant under increased vulnerability of water infrastructure, when state monitoring results should be used not only to describe the current state but also to identify reaches requiring priority control.

Recent Ukrainian studies demonstrate that surface water quality assessment should be linked to the concept of environmental risk. Bezsonnyi and Nekos [1] showed that under military danger the priority pollutants in surface runoff and river waters increasingly include organoleptic indicators and nitrogen-containing compounds that can deteriorate aquatic ecosystems and accelerate eutrophication. Bezsonnyi, Plyatsuk, Ponomarenko, and Tretyakov [2] substantiated the use of entropy-weighted water quality indices, because treating all parameters as equivalent or assigning weights solely by expert judgement may lead to the loss of important information. In the study by Bezsonnyi [3], surface-water risk assessment was related to the frequency of exceedance of maximum permissible concentrations for individual components, which is methodologically close to the present article, where exceedance ratios and violation frequencies are used for screening-based ranking of monitoring sites.

The contemporary international literature confirms that integral water quality indices remain convenient tools for summarizing complex hydrochemical data, but they require transparent selection of parameters, regulatory reference values, and weighting procedures. The critical review by Gupta and Gupta [4] emphasizes the evolution of the Water Quality Index and methodological limitations related to subjectivity in selecting weights and scales. Reviews by Chidiac et al. [5] and Mogane et al. [6] show that WQI facilitates communication of monitoring results to decision-makers, but different index schemes may classify the same water body differently. Akhtar et al. [7] proposed improving WQI calculation using multi-criteria decision-making, while the review by Muniz and Oliveira-Filho [8] summarizes the use of multivariate statistical analysis in water-quality studies. Accordingly, outdated historical approaches of previous decades were not used in this study; instead, the methodological basis was formed from modern index, factor, and cluster analytics presented in Scopus-indexed publications from 2021–2025.

Empirical studies of river and catchment systems in recent years demonstrate the effectiveness of combining WQI, PCA, cluster analysis, discriminant analysis, and GIS visualization. El Azhari et al. [9] combined WQI, multivariate statistics, and GIS for the Mediterranean Oued Laou watershed, which enabled interpretation of anthropogenic influence and the spatial structure of water quality. Wang et al. [10] applied multivariate statistical techniques to assess water quality in the Yuqiao Reservoir watershed and apportion pollution sources. Yao et al. [11] demonstrated the suitability of hydrochemical analysis, PCA, and clustering for evaluating spatial heterogeneity of waters, while Mammeri et al. [12] used WQI and discriminant analysis to identify indicators responsible for spatial differentiation of surface water quality. For the Rokel River, Barrie et al. [13] combined PCA, WQI, cluster analysis, and ANOVA, which is close to the logic of the present study, where multiyear mean concentrations are considered together with clustering similarity among sites. Gaur et al. [14] demonstrated the potential of combining WQI, hydrogeochemical interpretation, and PCA for surface waters in a mountainous region.

A separate group of recent publications addresses long-term monitoring series, seasonal variability, and selection of priority control reaches. Zhalmagambetova et al. [15] used a ten-year dataset containing 26 chemical components at 26 sites in the Irtysh River Basin and showed

that WQI and multivariate statistics are suitable for identifying zones of priority environmental regulation. Akiner, Chauhan, and Singh [16] combined CCME-WQI, factor analysis, PCA, and cluster analysis for long-term series in the Betwa River Basin, providing a direct methodological analogue for multiyear Southern Bug data. Roy et al. [17] developed a PCA-oriented WQI model for rivers in Dhaka and showed that principal components can reduce subjectivity in parameter selection. Hammoumi et al. [18] confirmed the importance of seasonal data stratification in combination with WQI and PCA. Jo et al. [19] used WQI and multivariate statistical techniques to identify key pollutants in standard watersheds within the TMDL policy framework. Alfaleh, Ben Khedher, and Alviz-Meza [20] substantiated the potential of entropy-weighted WQI and factor analysis for reducing the subjectivity of index-based assessment.

An important addition to this research direction is the study by Bezsonnyi, Tretyakov, Plyatsuk, Ponomarenko, and Davydova [21], in which an entropy-weighted water quality index was applied to more than 540 state surface-water monitoring sites in Ukraine. The authors revealed pronounced seasonal and spatial heterogeneity in surface water quality: better index values were recorded in winter and spring, whereas the most stressed conditions occurred during low-flow and autumn periods; among the most problematic regions, the Southern Bug Basin was specifically identified.

A closely related and more recent contribution is the basin-scale study by Bezsonnyi [22], which applied the same entropy-weighted approach specifically to the Southern Bug River basin, using hydrochemical observations from 36 monitoring stations for 2020–2024 and twelve water-quality parameters. The author established a pronounced downstream and seasonal gradient of degradation: EWQI values increased from clean conditions (Classes II–III) in the upper reaches near Haivoron and Ladyzhyn to very and extremely polluted conditions (Classes VI–VII, EWQI > 3.0) in the estuarine section near Mykolaiv, with the basin-mean index rising from 1.85 in the cold period to 2.46 in the warm period, a 33% seasonal deterioration confirmed by the Mann–Whitney test ($p < 0.01$). Entropy-weight and principal component analyses identified ammonium (22%), phosphates (18%), and BOD_5 (15%) as the dominant contributors to the index, while k-means clustering delineated four water-quality zones ranging from clean headwaters to a critically polluted estuarine cluster. This study confirms, at the basin scale, the priority role of biogenic and organic pollution already indicated by the nationwide assessment [21] and demonstrates the practical feasibility of combining entropy weighting, PCA, and clustering for the Southern Bug. At the same time, it relies on a comparatively short five-year record (2020–2024) and does not apply a regulatory exceedance-frequency framework or robust outlier-control standardization, which leaves room for the longer-term, regulation-oriented profiling addressed in the present study.

This directly substantiates the need for a more detailed basin-scale analysis of the Southern Bug that combines seasonality, spatial differentiation, and regulatory interpretation. The European context of such work is framed by studies assessing river ecological status in line with the Water Framework Directive. Naddeo et al. [23], using 34 rivers in the Salerno Province as a case study, demonstrated the practical role of aggregated macro-pollution indicators for evaluating river-water status, while Wuijts et al. [24] emphasized that achieving WFD objectives requires not only monitoring but also cross-sectoral river-basin management. The development of data-driven approaches should also be considered: the review by Zhu et al. [25] shows that machine learning is increasingly used for classification, forecasting, and optimization of water-quality monitoring, whereas Uddin et al. [26] demonstrate that outliers and the quality of input data can affect water categorization in index models. Therefore, long state monitoring series require robust standardization, control of technical extremes, and transparent justification of index classes.

The regulatory and institutional framework of the study is based on the state surface-water monitoring system of Ukraine. The State Water Agency defines it as a system for collecting, processing, summarizing, and analysing information on the condition of water bodies in order to forecast changes and prepare scientifically grounded management recommendations [27]. At the same time, official assignment of surface-water bodies to ecological and chemical status classes is regulated by the Methodology approved by Order No. 5 of the Ministry of Environmental Protection of Ukraine dated 14 January 2019 [28]. This article does not perform full official classification of the ecological status of water bodies, because that procedure requires not only physical-chemical but also biological and hydromorphological indicators. Instead, a screening hydrochemical assessment is applied through the ratio and frequency of exceedance of regulatory reference values formed with due regard to hygienic water-quality standards [29] and methodological recommendations on maximum permissible discharge standards [30]. The European context is set by the EU Water Framework Directive, which establishes the river-basin management principle and the requirement to achieve good water status [31].

Thus, the current state of research indicates five methodological requirements for analysing long-term hydrochemical series. First, results should be interpreted in regulatory terms rather than remain merely statistically descriptive. Second, integral indices should have a transparent formula, an understandable weighting system, or a justified decision not to apply weighting. Third, multivariate statistics should be used to test the internal structure of the data and identify typical profiles. Fourth, seasonality and spatiality should be analysed jointly, because hydrochemical indicators strongly depend on water availability, thermal regime, dilution, and local sources of substance inputs. Fifth, long monitoring series require data-quality control, detection of technical extremes, and robust standardization procedures so that isolated anomalous values do not determine cluster structure or index-based ranking.

For the Southern Bug Basin, such an integrated scheme remains insufficiently represented in the open scientific literature: existing approaches generally either assess individual water-quality indices, apply multivariate statistics without comprehensive regulatory profiling, or consider Ukraine at a generalized inter-basin level. Therefore, combining multiyear mean concentrations, seasonal profiles, ratios of exceedance of regulatory reference values, robust data preparation, PCA visualization, and clustering of monitoring sites provides a justified methodological basis for identifying organic-oxygen, nutrient, and mineralization-salinity profiles within this basin.

The purpose of the study is to perform factor-cluster and regulatory-index profiling of long-term hydrochemical series for rivers of the Southern Bug Basin in order to identify sites dominated by organic, nutrient, or mineralization-salinity pollution and to rank reaches by hydrochemical risk level. The object of the study is surface waters of rivers in the Southern Bug Basin. The subject of the study is the long-term structure of hydrochemical indicators, their seasonal variability, regulatory exceedances, and cluster profiles of monitoring sites.

Materials and Methods

The analysis was based on processed data from the state surface-water monitoring system of the State Water Agency of Ukraine. From the general dataset, records with Riverbas_Name = “Southern Bug” were selected. The resulting sample contains 5,654 records for 13 January 2003–18 March 2026 from 95 monitoring sites. The analysis included BOD5, suspended solids, dissolved oxygen, sulphates, chlorides, ammonium nitrogen, nitrates, nitrites, phosphates, surfactants, permanganate oxidizability, COD, atrazine, and simazine. The “total nitrogen” indicator contained no filled values in the selected fragment and was not used in calculations. General principles of handling laboratory-control data, harmonizing measurement units, and ensuring sample traceability were aligned with current standards for hydrochemical analysis and sampling/preservation of water samples [32, 33].

At the stage of physical-chemical plausibility control, 57 obviously technical values were removed at the level of individual data cells. Technical extremes were defined as values exceeding a realistic range for surface waters by one or several orders of magnitude or contradicting the analytical nature of the indicator, including values of approximately 40–45 thousand for indicators originally measured in mg/dm^3. For dissolved oxygen, values above 20 mg/dm^3 were additionally reviewed as potentially related to data-entry errors, because without accompanying information on temperature, saturation, and measurement methodology they cannot be unambiguously used in index calculations (Table 1).

Table 1

Control of technical extremes in the Southern Bug basin sample

Indicator	Removed values	Minimum removed value	Maximum removed value
BOD5	2	44562.0	45323.0
Suspended solids	2	45392.0	45394.0
Dissolved oxygen	25	20.24	45748.0
Sulphates	0	-	-
Chlorides	2	5076.4	5615.3
Ammonium nitrogen	0	-	-
Nitrates	3	45324.0	45383.0
Nitrites	11	10.58	109.0
Phosphates	2	406.0	45474.0
Surfactants	0	-	-
Permanganate oxidizability	7	320.0	43800.0
COD	3	4068.0	45443.0
Atrazine	0	-	-
Simazine	0	-	-

The stability check showed that removal of technical extremes did not change the overall structure of the conclusions: the leading indicator groups, the balance among organic, nutrient, and mineralization-salinity profiles, and the list of priority reaches remained interpretatively stable. General principles of data-quality control and laboratory-analytical reproducibility were aligned with current guidance on water analysis and sample handling [32; 33].

For each site p and indicator j, the multiyear mean concentration was calculated as follows:

$$\bar{C}pj = (1 / npj) \cdot \Sigma Cipj \quad (1)$$

where $\bar{C}pj$ is the mean concentration of indicator j at site p;
$Cipj$ is an individual observation;
npj is the number of measurements for the corresponding "site–indicator" pair.

The seasonal profile was calculated separately for winter, spring, summer, and autumn:

$$\bar{C}pjs = (1 / npjs) \cdot \Sigma Cipjs \quad (2)$$

where s is the season.

This scheme allows winter and summer low-flow periods, spring dilution, and autumn runoff-formation conditions to be distinguished.

Regulatory interpretation was based on the exceedance ratio relative to a regulatory reference value. For indicators for which an increase in concentration is hazardous, the following expression was used:

$$Kij = Cij / Nj \quad (3)$$

where Kij is the exceedance ratio or the degree of approach to the reference value;
Cij is the measured concentration;
Nj is the regulatory value.

For dissolved oxygen, the inverse principle was used: a violation was recorded when concentration was lower than the minimum acceptable reference value.

$$K(O_2) = N_{min(O_2)} / C(O_2), \text{ if } C(O_2) < N_{min(O_2)} \quad (4)$$

The violation frequency for indicator j at a site or in the entire basin was determined as:

$$Fj = (mj / nj) \cdot 100\ \% \quad (5)$$

where mj is the number of samples with an exceedance/violation of the reference value, and nj is the number of samples with an available value for the indicator.

For ranking of sites, a modified regulatory index $I6$ was used; it was constructed as the mean of the six highest partial ratios K at a monitoring site:

$$I6p = (1 / 6) \cdot \Sigma Kp(r),\ r = 1...6,$$
$$Kp(r) \text{ are the six highest } K \text{ values at site } p \quad (6)$$

The $I6$ index was used as an author-defined screening tool for ranking sites by hydrochemical risk. It is not an official water-quality index and does not replace the assignment of surface-water bodies to ecological or chemical status classes. In equation (6), $Kp(r)$ denotes the six highest mean partial exceedance ratios for site p across all indicators used; ranking was performed separately for domestic-use and fishery-use reference values. Using the six highest partial ratios prevents risk from being "diluted" by a large number of less relevant indicators while preserving comparability among sites. The following screening classes were used for I6: $I \leq 1$ – conditionally low risk; $1 < I \leq 2.5$ – moderate risk; $2.5 < I \leq 4$ – significant risk; $4 < I \leq 6$ – high risk; $I > 6$ – critical risk (Table 2).

All indicators were preliminarily grouped into three analytical blocks: organic-oxygen, nutrient, and mineralization-salinity. Block scores were calculated as mean partial ratios K for the corresponding indicators. This index-cluster logic is consistent with modern approaches that combine WQI, PCA, cluster analysis, and multivariate statistics in hydrochemical studies [8; 15; 16; 17; 18]. To stabilize distributions, a $log(1 + x)$ transformation was applied, after which the data were scaled robustly using the median and the interquartile range:

$$Zij = [log(1 + Xij) - Mej] / IQRj \quad (7)$$

where Zij is the robustly standardized value;
Xij is a block or indicator score;
Mej is the median;
$IQRj$ is the interquartile range.

Principal component analysis was used not as a self-sufficient procedure for official water-quality classification, but as a tool for visualizing the variation structure of the three block indicators. Monitoring sites were clustered by the k-means algorithm in the space of organic-oxygen, nutrient, and mineralization-salinity blocks. The objective function of the algorithm is:

$$arg\ min\ \Sigma k\ \Sigma p \in Sk\ ||Zp - \mu k||^2 \quad (8)$$

To select the number of clusters, variants $K = 2–5$ were tested. The final decision in favour of $K = 3$ was made not only on the basis of the

Table 2

Regulatory reference values used for screening assessment

Indicator	Analytical block	Domestic-use reference value, mg/dm³	Fishery-use reference value, mg/dm³	Use in assessment
BOD5	organic block	≤ 6	≤ 3	direct ratio K = C/N
COD	organic block	≤ 30	≤ 30	direct ratio
Permanganate oxidizability	organic block	≤ 10	≤ 10	direct ratio
Dissolved oxygen	oxygen regime	≥ 4	≥ 6	violation due to oxygen deficit
Ammonium nitrogen	nutrient block	≤ 2.0	≤ 0.5	direct ratio
Nitrates	nutrient block	≤ 45	≤ 40	direct ratio
Nitrites	nutrient block	≤ 3.3	≤ 0.08	direct ratio
Phosphates	nutrient block	≤ 3.5	≤ 2.14	direct ratio
Sulphates	mineralization-salinity block	≤ 500	≤ 100	direct ratio
Chlorides	mineralization-salinity block	≤ 350	≤ 300	direct ratio
Surfactants	additional anthropogenic block	≤ 0.5	≤ 0.1	direct ratio

Note. The regulatory reference values presented here were used only for screening assessment of exceedance ratios and violation frequencies. They are not a procedure for officially assigning surface-water bodies to ecological or chemical status classes. Domestic-use and fishery-use reference values were applied as comparable regulatory thresholds for index-based ranking of sites, while results were interpreted as hydrochemical risk based on physical-chemical indicators.

Table 3

Testing the number of clusters using the silhouette coefficient

K	Silhouette score	Group sizes	Methodological interpretation
2	0.839	46; 2	highest coefficient, but excessive merging of most sites
3	0.583	43; 3; 2	selected as the optimal compromise between statistical quality and ecological interpretability
4	0.388	24; 20; 2; 2	artificial splitting of the baseline organic-oxygen profile
5	0.434	24; 13; 7; 2; 2	formation of unstable small groups and more complicated ecological interpretation

silhouette coefficient, but by combining statistical quality, grouping stability, and ecological interpretability of the profiles (Table 3).

The $K = 2$ variant had the highest silhouette coefficient, but it excessively merged 46 of 48 sites into one class. The $K = 3$ variant retained an acceptable silhouette coefficient of 0.583 and enabled interpretation of three ecologically meaningful profiles: organic-oxygen, nutrient, and mineralization-salinity.

Results

The Southern Bug Basin sample covers 5,654 records and 95 monitoring sites. For regulatory ranking and clustering, 48 sites with sufficient repetition of observations were selected. This approach reduces randomness associated with single or sparse observations and enables representative hydrochemical profiles to be formed.

Regulatory exceedances. Under domestic-use regulatory reference values, exceedances were most frequently found for indicators of the organic block: COD, permanganate oxidizability, and BOD5 (Table 4, Fig. 1).

This indicates that, at the basin scale, the organic-oxygen component is the leading component of hydrochemical pressure. Mineralization-salinity pollution appears more locally, but for certain lower reaches of the Southern Bug and Inhul Rivers it reaches high chloride and sulphate ratios. A graphical summary of these violation frequencies is provided in Fig. 1.

Figure 1 clearly confirms that the largest shares of exceedances are concentrated in indicators of the organic block.

Comparison with fishery-use reference values substantially strengthens the assessment of pressure (Table 5).

The highest shares of violations were found for BOD5, COD, sulphates, permanganate oxidizability, nitrites, and ammonium nitrogen. Thus, for protecting aquatic ecosystems, organic and nutrient loading should be treated as priorities. A visual comparison of violation shares is presented in Fig. 2.

Figure 2 shows that fishery-use regulatory reference values reveal a broader spectrum of problematic indicators than domestic-use reference values.

Table 4

Frequency of exceedance of domestic-use regulatory reference values

Indicator	Reference value	n	Violations	Share, %	Maximum ratio
COD	30.0	4972	2134	42.90	9.390
Permanganate oxidizability	10.0	4017	1640	40.80	7.800
BOD5	6.0	4983	735	14.80	8.480
Sulphates	500.0	4893	293	6.000	7.150
Ammonium nitrogen	2.0	4983	179	3.600	19.71
Dissolved oxygen	≥ 4	5183	183	3.500	13.33
Chlorides	350.0	4891	153	3.100	13.60
Phosphates	3.5	4976	32	0.600	3.970
Nitrites	3.3	4971	27	0.500	2.180
Nitrates	45.0	4982	20	0.400	2.960
Surfactants	0.5	4355	8	0.200	2.740

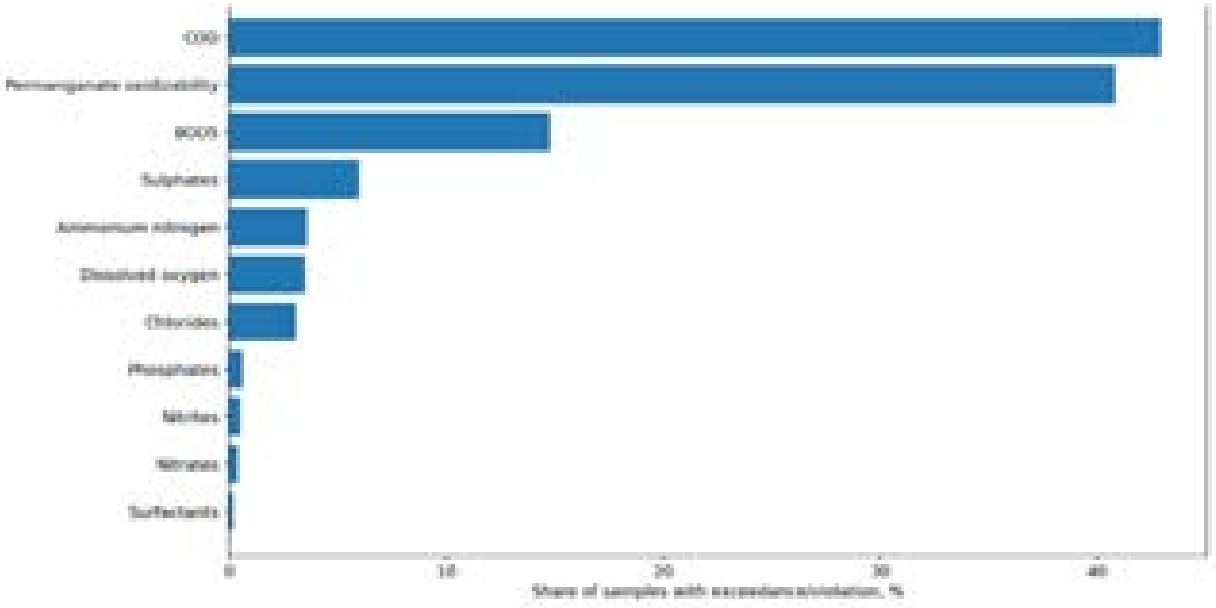


Fig. 1. Share of samples exceeding domestic-use regulatory reference values.

Seasonal hydrochemical profiles. Seasonal analysis shows that the organic block retains an increased role during the warm period, when mean COD and BOD_5 values combine with a decrease in dissolved oxygen concentration (Table 6).

In summer, the mean oxygen concentration was 7.597 mg/dm³ compared with 10.803 mg/dm³ in winter. This is consistent with higher water temperature, intensification of biochemical oxygen demand, and seasonal bioproduction processes. The dynamics of the organic block are shown in Fig. 3.

Table 5

Frequency of exceedance of fishery-use regulatory reference values

Indicator	Reference value	n	Violations	Share, %	Maximum ratio
BOD5	3.0	4983	3011	60.40	16.97
COD	30.0	4972	2134	42.90	9.390
Sulphates	100.0	4893	2077	42.40	35.73
Permanganate oxidizability	10.0	4017	1640	40.80	7.800
Nitrites	0.08	4971	1565	31.50	90.00
Ammonium nitrogen	0.5	4983	939	18.80	78.85
Dissolved oxygen	≥ 6	5183	700	13.50	20.00
Surfactants	0.1	4355	267	6.100	13.70
Chlorides	300.0	4891	160	3.300	15.86
Phosphates	2.14	4976	95	1.900	6.490
Nitrates	40.0	4982	35	0.700	3.330

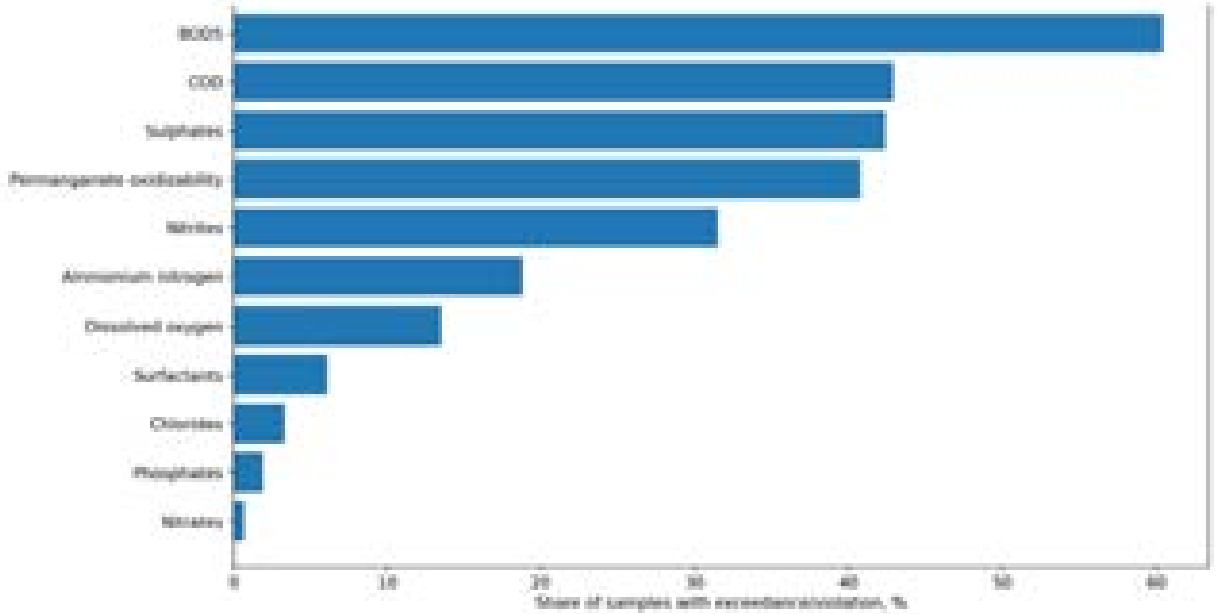


Fig. 2. Share of samples exceeding fishery-use regulatory reference values.

Figure 3 demonstrates higher COD and permanganate oxidizability during the warm period against the background of relatively stable mean BOD5 values.

Seasonal changes in nutrient indicators are shown in Fig. 4.

Figure 4 indicates a marked decrease in nitrates in summer together with a local increase in nitrites and phosphates.

Table 6

Seasonal mean concentrations of the main indicators, mg/dm³

Season	BOD_5	O_2	COD	Permang. oxid.	NH_4	NO_3	NO_2	PO_4	SO_4	Cl	Surfactants
Winter	3.179	10.80	27.74	9.910	0.559	6.719	0.134	0.425	165.5	102.7	0.037
Spring	4.108	10.16	28.45	11.71	0.551	5.374	0.130	0.289	146.4	90.63	0.042
Summer	4.078	7.597	31.23	11.70	0.512	3.042	0.141	0.552	168.1	107.3	0.042
Autumn	4.025	8.425	30.14	12.71	0.573	3.810	0.193	0.453	155.5	143.6	0.043

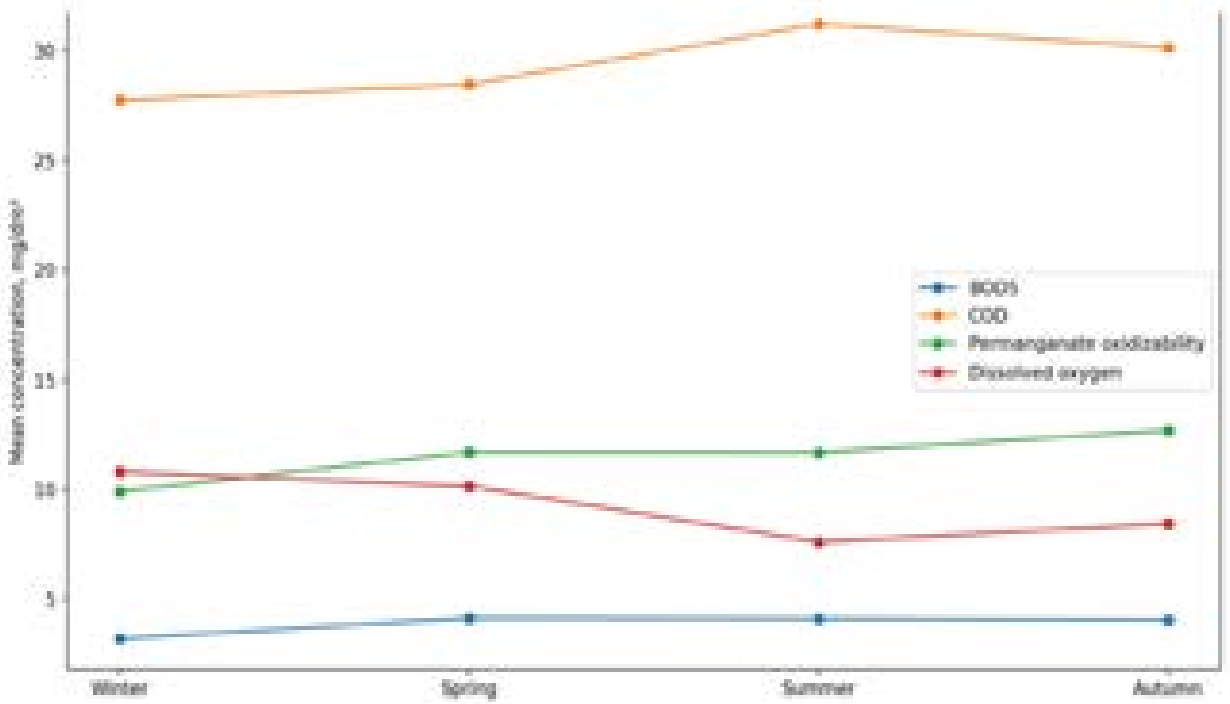


Fig. 3. Seasonal profile of the organic block.

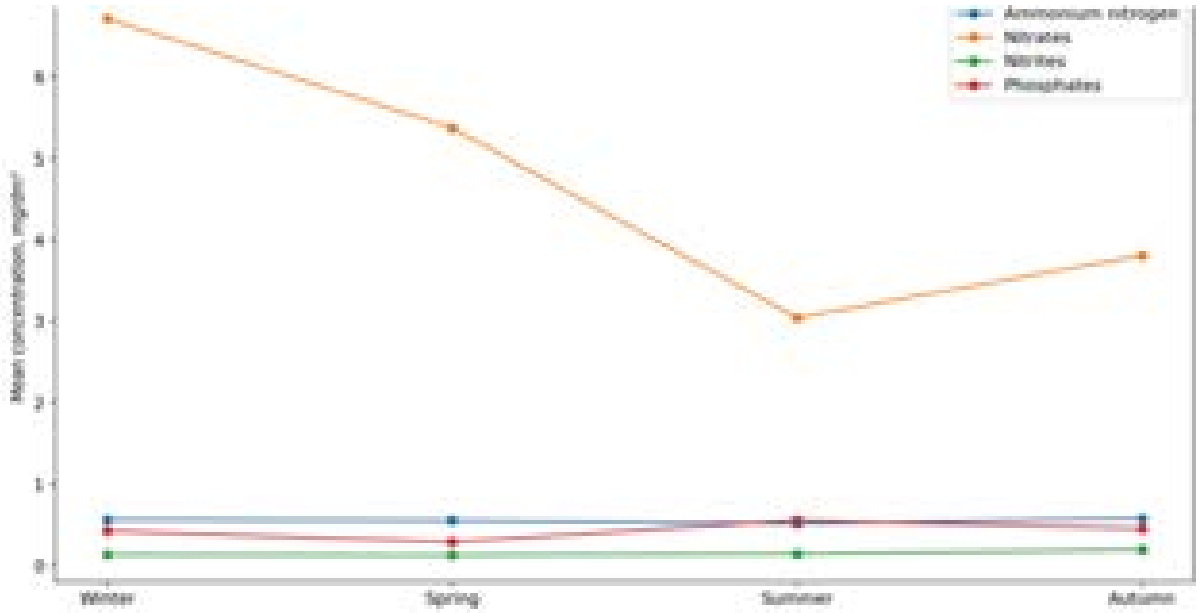


Fig. 4. Seasonal profile of the nutrient block.

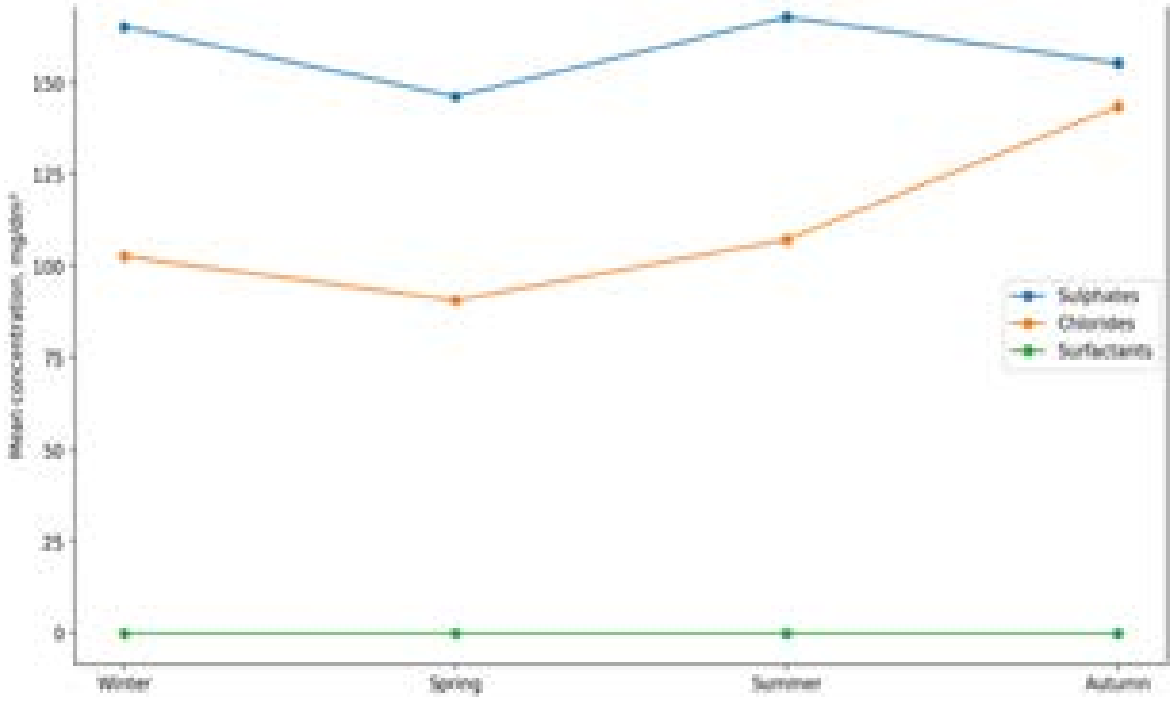


Fig. 5. Seasonal profile of the mineralization-salinity block.

The dynamics of the mineralization-salinity block are presented in Fig. 5.

Figure 5 highlights an increase in chlorides in autumn and relatively high mean sulphate concentrations during the summer period.

PCA visualization in the space of three block scores showed that the first component explains 80.4% of the variation and primarily reflects the nutrient gradient, whereas the second component explains 13.5% and is associated with the mineralization-salinity gradient. This result should not be interpreted as a full official factor classification of water bodies; it was used for graphical confirmation that differentiation among the most problematic sites is driven primarily by nutrient and salinity components.

Quantitative loadings of the block indicators on the first two principal components are presented in Table 7.

As shown in Table 7, PC1 almost entirely reflects the nutrient block, whereas PC2 is associated with the mineralization-salinity block.

Summary characteristics of the identified cluster profiles are presented in Table 8.

Table 8 shows that the mineralization-salinity profile has the highest mean I6 index, whereas the organic-oxygen profile includes the overwhelming majority of monitoring sites.

Table 7

Loadings of block indicators on principal components

Block	PC1	PC2
Organic-oxygen	0.036	0.102
Nutrient	0.999	0.028
Mineralization-salinity	-0.032	0.994

Table 8

Cluster hydrochemical profiles of monitoring sites

Profile	Number of sites	Mean I6	Mean organic block	Mean nutrient block	Mean mineral block
organic-oxygen profile	43	0.720	0.926	0.102	0.275
mineralization-salinity profile	3	1.561	1.158	0.179	2.318
nutrient profile	2	1.387	0.957	1.246	0.110

Graphical clustering of monitoring sites in the space of block hydrochemical profiles is presented in Fig. 6.

Figure 6 visualizes the separation of two small clusters with distinct nutrient and mineralization-salinity features from the main group of sites.

The spatial positions of the sites belonging to each cluster are shown in Fig. 7.

The organic-oxygen profile includes 43 sites and represents the baseline pressure structure for the basin. The nutrient profile covers two sites in the upper Southern Bug: downstream of Khmelnytskyi and in the Medzhybizh Reservoir area. The mineralization-salinity profile is represented by three sites, including the lower Southern Bug in the Bug Estuary area, the Inhul River in Mykolaiv, and the Kodyma River near Balta. This structure corresponds to spatial changes in pressure sources: from nutrient influence in upper urbanized reaches to higher mineralization in the lower part of the basin.

The I6 index based on domestic-use reference values showed that most representative sites belong to screening class I, whereas six sites fall into class II, i.e. moderate hydrochemical risk. The highest values were characteristic of the Bug Estuary within Mykolaiv, the lower Inhul River in Mykolaiv, the upper Southern Bug downstream of Khmelnytskyi, the Medzhybizh Reservoir, the Kodyma River near Balta, and

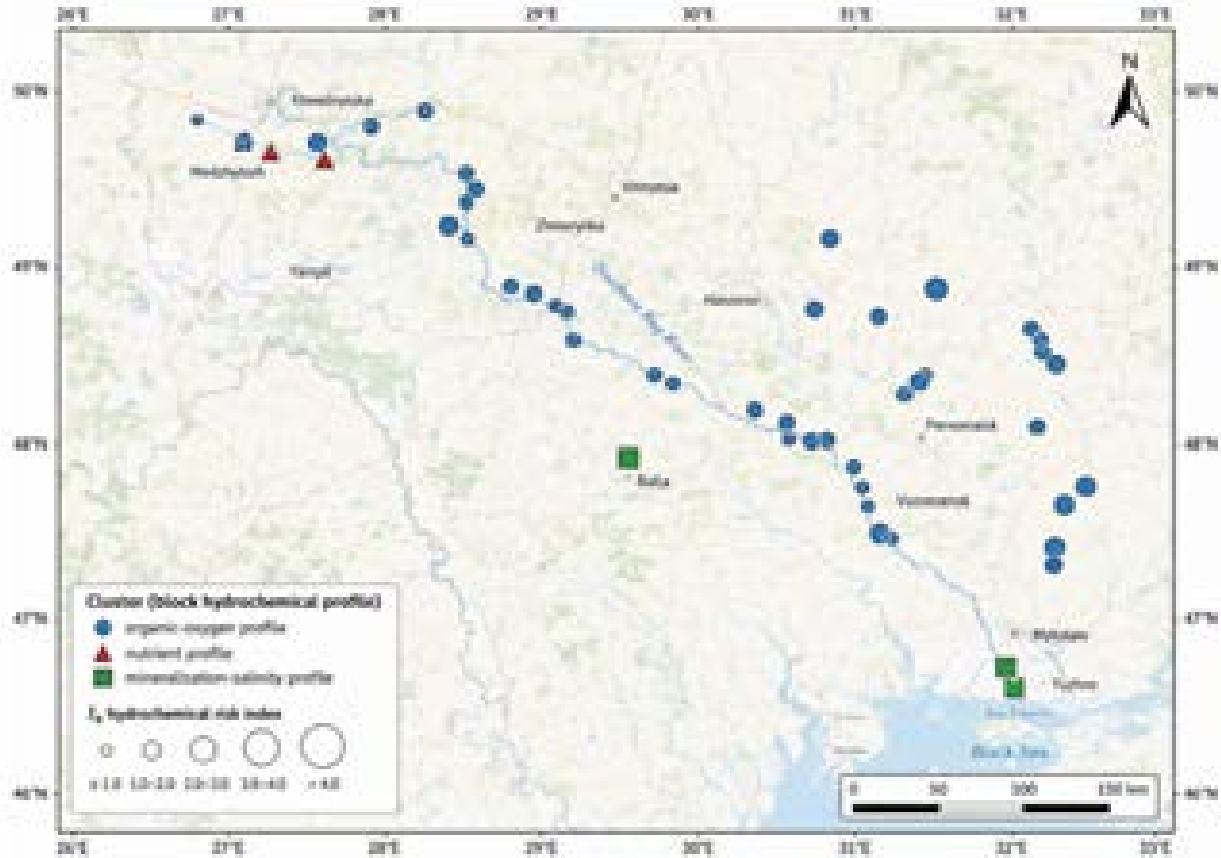


Fig. 6. Clustering of monitoring sites by block hydrochemical profiles.

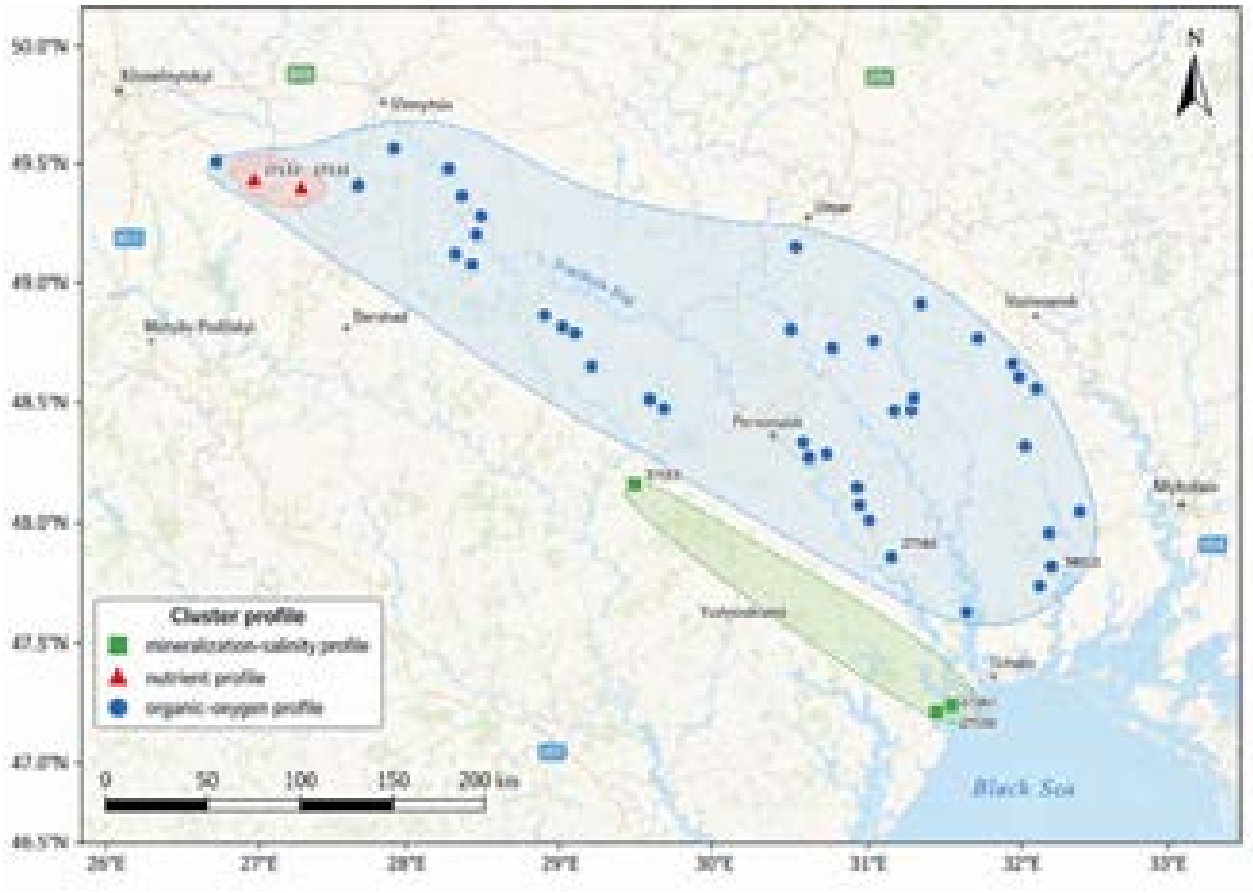


Fig. 7. Spatial scheme of monitoring sites by clusters.

the reach downstream of the discharge of Vinnytsiavodokanal.

Ranking of sites according to domestic-use regulatory reference values is detailed in Table 9.

Table 9 shows that the maximum I6 values are formed both in the lower part of the basin and at selected upper reaches of the Southern Bug.

For a visual comparison of these sites by I6 magnitude, Fig. 8 is used.

Figure 8 confirms that, under domestic-use reference values, differences among the leading sites are moderate, although spatially they cover different parts of the basin.

Under fishery-use reference values, the picture is substantially stricter: one site belongs to screening class V, one to class IV, three to class III, and most problematic reaches move into class II. This demonstrates that ecosystem-oriented

Table 9

Sites with the highest I6 index according to domestic-use reference values

Site ID	Monitoring site	n	I6	Risk class	Limiting indicator	Maximum K
27150	Southern Bug River, 0.5 km, Mykolaiv, Bug Estuary, industrial water intake of Mykolaiv CHP (left part of the seaport)	64	1.852	II – moderate risk	chlorides	6.010
27167	Inhul River, 2 km, Mykolaiv, 2 Naberezhna Street, old pedestrian bridge across the Inhul River	51	1.633	II – moderate risk	chlorides	4.475
27132	Southern Bug River, 744 km, Kopystyn village, downstream of Khmelnytskyi	71	1.555	II – moderate risk	ammonium nitrogen	4.588
27133	Southern Bug River, 711 km, Medzhybizh urban-type settlement, Medzhybizh Reservoir	67	1.219	II – moderate risk	ammonium nitrogen	3.283
27153	Kodyma River, 103 km, Balta, agricultural water intake	80	1.197	II – moderate risk	permanganate oxidizability	2.427
27138	Southern Bug River, 569.5 km, 500 m downstream of the Vinnytsiavodokanal discharge (1.5 km downstream of the Sabariv Reservoir dam)	170	1.014	II – moderate risk	permanganate oxidizability	2.105

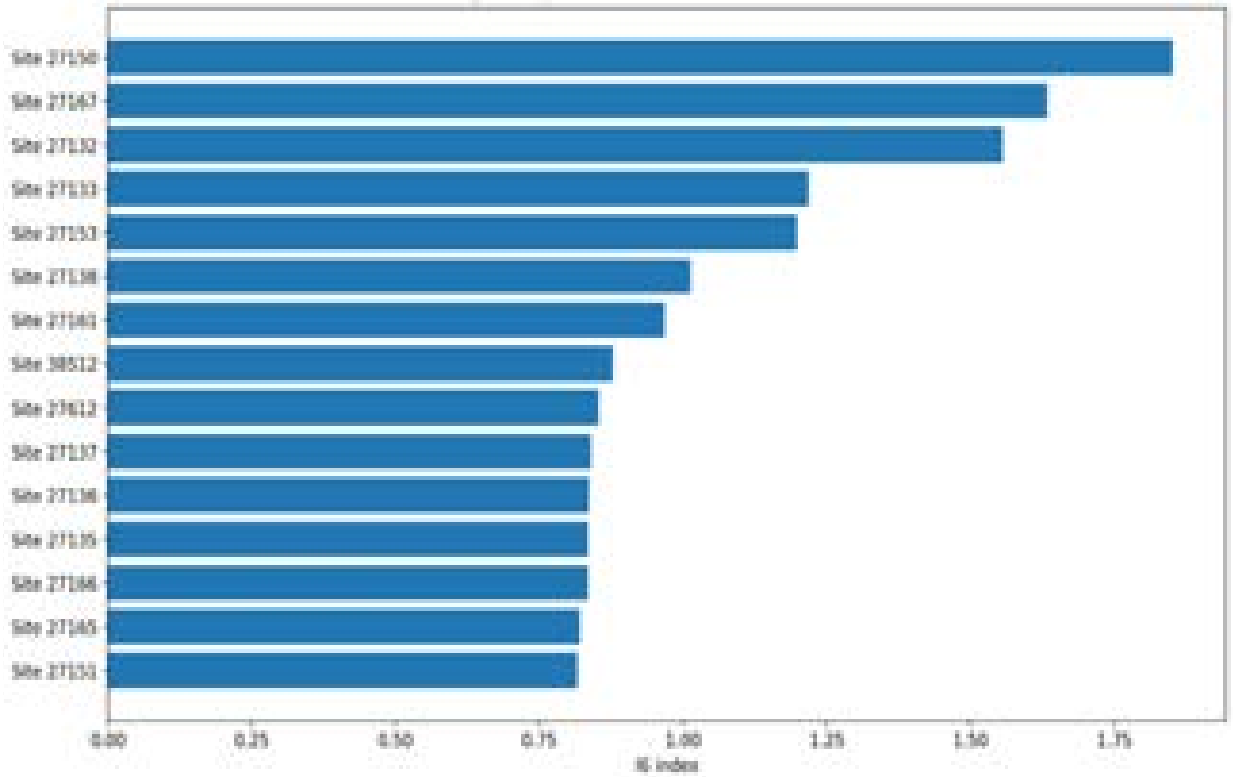


Fig. 8. Sites with the highest hydrochemical risk according to domestic-use reference values.

assessment is more sensitive to nutrient forms of nitrogen, BOD5, sulphates, and oxygen deficit.

Sites with the highest I6 values under fishery-use reference values are systematized in Table 10.

Table 10 demonstrates a sharp increase in the I6 index in the upper Southern Bug, where ammonium nitrogen acts as the limiting factor.

Graphical ranking of these sites is presented in Fig. 9.

Figure 9 demonstrates that the fishery-use approach substantially increases the contrast between the most problematic and background monitoring sites.

Discussion

The obtained results demonstrate that the long-term monitoring series for the Southern Bug should be interpreted not only through mean concentrations, but through the combined analysis of regulatory exceedance frequency, seasonality, and site typology. If the analysis were limited to mean concentrations alone, some problematic reaches with high exceedance frequencies or high peak ratios would remain insufficiently highlighted. Therefore, the I6 index, which focuses on the six most problematic partial ratios, is a useful screening tool.

Table 10

Sites with the highest I6 index according to fishery-use reference values

Site ID	Monitoring site	n	I6	Risk class	Limiting indicator	Maximum K
27132	Southern Bug River, 744 km, Kopystyn village, downstream of Khmelnytskyi	71	7.003	V – critical risk	ammonium nitrogen	18.35
27133	Southern Bug River, 711 km, Medzhybizh urban-type settlement, Medzhybizh Reservoir	67	4.678	IV – high risk	ammonium nitrogen	13.13
27150	Southern Bug River, 0.5 km, Mykolaiv, Bug Estuary, industrial water intake of Mykolaiv CHP (left part of the seaport)	64	2.743	III – significant risk	chlorides	7.011
27153	Kodyma River, 103 km, Balta, agricultural water intake	80	2.694	III – significant risk	nitrites	6.773
27138	Southern Bug River, 569.5 km, 500 m downstream of the Vinnytsiavodokanal discharge (1.5 km downstream of the Sabariv Reservoir dam)	170	2.539	III – significant risk	nitrites	6.681

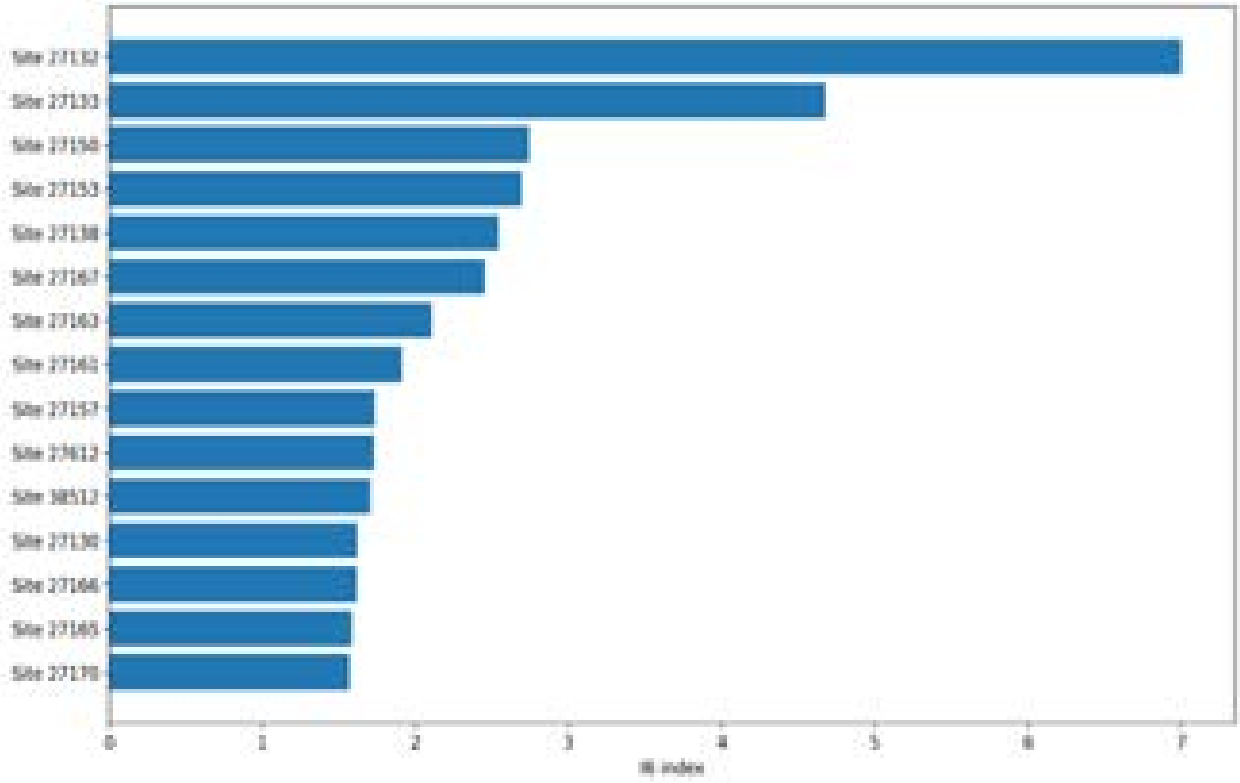


Fig. 9. Sites with the highest hydrochemical risk according to fishery-use reference values.

Dominance of the organic-oxygen profile at most sites does not imply the same state for the entire basin system. On the contrary, this result should be interpreted as a background structural feature of long-term hydrochemical data, onto which nutrient or mineralization-salinity deviations are locally superimposed. For reaches downstream of large settlements, increased BOD5, COD, permanganate oxidizability, and nitrogen forms are logical. For the lower part of the basin and estuarine zone, a stronger role of chlorides and sulphates is expected and may be associated with both natural-hydrological and anthropogenic factors.

The nutrient profile identified for upper Southern Bug sites has particular ecological significance. Increased ammonium nitrogen, nitrites, and phosphates may act as preconditions for eutrophication, deterioration of oxygen regime, and changes in biotic condition. In this respect, the results are consistent with previous studies in which nitrogen-containing substances were considered priority pollutants under increased environmental risk.

Comparison of domestic-use and fishery-use reference values reveals a methodologically important difference. Under domestic-use reference values, a substantial share of sites has low or moderate screening risk. Under fishery-use reference values, the picture is considerably more stressed, because aquatic ecosystems are more sensitive to organic loading, oxygen deficit, nitrites, ammonium, and sulphates. Therefore, for environmental planning, both scales should be presented: the first characterizes the sanitary and household dimension, whereas the second reflects ecosystem vulnerability.

The applied methodology has several limitations. First, it does not replace the official ecological-status classification of surface-water bodies, because it does not include the full set of biological, hydromorphological, and priority chemical indicators. Second, state monitoring series have unequal repetition across sites and indicators, so only sites with a sufficient number of observations were selected for clustering. Third, the absence of discharge data and information on specific effluent releases does not allow the analysis to move from hydrochemical profiling to a full calculation of assimilative capacity or maximum permissible discharge. Fourth, technical extremes were removed at the level of individual values rather than entire samples; this minimizes information loss but requires preservation of the data-cleaning protocol in supplementary materials. At the same time, the stability check confirmed that the main cluster structure and the list of priority reaches do not depend on isolated obvious technical values. The resulting scheme is suitable for preliminary identification of reaches that require further detail in state monitoring programmes and river-basin management plans.

Conclusions

Based on processed state monitoring data for 2003–2026, 5,654 records from 95 monitoring sites were analysed for the Southern Bug Basin. After physical-chemical plausibility control, 57 obviously technical values were removed, which increased the reliability of mean, index-based, and cluster calculations.

Under domestic-use reference values, the most frequent exceedances were identified for COD (42.9% of samples), permanganate oxidizability (40.8%), and BOD5 (14.8%), indicating the leading role of organic loading in the overall structure of the basin hydrochemical profile.

Under fishery-use reference values, violation frequencies increase substantially: BOD5 – 60.4%, COD – 42.9%, sulphates – 42.4%, permanganate oxidizability – 40.8%, nitrites – 31.5%, and ammonium nitrogen – 18.8%. This confirms the higher sensitivity of ecosystem-oriented assessment to nutrient and organic pressure.

Seasonal profiles demonstrate a combination of increased organic indicators during the warm period with decreased dissolved oxygen. The summer mean oxygen concentration is lower than the winter mean, indicating seasonal stress of the oxygen regime.

Clustering of 48 representative sites, justified by testing K = 2–5 using the silhouette coefficient and ecological interpretability, identified three types of hydrochemical profiles: organic-oxygen (43 sites), mineralization-salinity (3 sites), and nutrient (2 sites). The organic-oxygen profile should be interpreted as a baseline structural feature of basin hydrochemical data rather than as uniformly high pollution at all sites in this group.

The modified regulatory index I6 enabled ranking of sites by hydrochemical risk. Under domestic-use reference values, the highest values were found for the Bug Estuary in Mykolaiv, the lower Inhul River in Mykolaiv, the upper Southern Bug downstream of Khmelnytskyi, the Medzhybizh Reservoir, the Kodyma River near Balta, and the reach downstream of the Vinnytsiavodokanal discharge.

The proposed scheme is a screening tool and does not substitute for official assignment of surface-water bodies to ecological-status classes. It is appropriate for identifying priority reaches for enhanced control, optimizing monitoring programmes, and preparing water-protection measures in the Southern Bug Basin.

Внесок авторів: всі автори зробили рівний внесок у цю роботу
Конфлікт інтересів: автори засвідчують, що, незважаючи на те, що один із авторів статті є членом редакційної колегії цього журналу, процес рецензування, прийняття рішення щодо публікації та редагування проводилися незалежно, без його участі чи впливу. Будь-які потенційні конфлікти інтересів були повністю усунені шляхом зовнішнього контролю процесу.
Декларація про використання генеративного штучного інтелекту: Автори використовували інструменти генеративного штучного інтелекту (GenAI) для допоміжної роботи: моделі ChatGPT-5.5 (OpenAI, 2026) виключно для мовного редагування, структурного впорядкування тексту; Grammarly – для перевірки правильності перекладу тексту, а також для виправлення граматичних та стилістичних помилок. Усі результати роботи з цими інструментами були ретельно контрольовані, перевірені та, за необхідності, відредаговані авторами. Весь науковий контент, матеріали та висновки були створені авторами. Автори несуть повну відповідальність за зміст та цілісність публікації.

Author Contributions: All authors contributed equally to this work
Conflict of Interest: The authors certifies that, although one of the authors of the article is a member of the editorial board of this journal, the peer review, publication decision, and editorial processes were conducted independently, without their participation or influence. Any potential conflicts of interest were fully mitigated through external oversight of the process.
Declaration of use of generative artificial intelligence: The authors utilized generative artificial intelligence (GenAI) tools in a supportive capacity: the ChatGPT-5.5 model (OpenAI, 2026) exclusively for language editing and structural text organization; Grammarly – to verify the correctness of the text translation, as well as to correct grammatical and stylistic errors. All outputs from these tools were carefully supervised, reviewed, and, where necessary, edited by the authors. All scientific content, materials, and conclusions were created by the authors. The authors retain full responsibility for the content and integrity of the publication.

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Факторно-кластерне профілювання якості вод Південного Бугу

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АНОТАЦІЯ

Метою дослідження є факторно-кластерне та нормативно-індексне профілювання багаторічних гідрохімічних рядів річок басейну Південного Бугу для виділення ділянок із домінуванням органічного, біогенного або мінералізаційно-сольового забруднення та ранжування пунктів державного моніторингу за рівнем гідрохімічного ризику. Вихідною базою стали оброблені дані державного моніторингу поверхневих вод Держводагентства за 2003–2026 рр. Використано розрахунок середніх багаторічних концентрацій, сезонних профілів, частоти та кратності перевищення нормативних орієнтирів, модифікований нормативний індекс I6, аналіз головних компонент і кластеризацію за блоковими гідрохімічними профілями. Методична схема адаптує сучасний індексно-факторно-кластерний підхід до умов багаторічних моніторингових рядів. У межах басейну Південного Бугу відібрано 5654 записи з 95 пунктів спостережень за період з 13.01.2003 до 18.03.2026. Після контролю фізико-хімічної правдоподібності вилучено 57 очевидно технічних значень. За господарсько-побутовими орієнтирами найчастіші перевищення встановлено для ХСК (42,9 % проб), перманганатної окиснюваності (40,8 %) і БСК5 (14,8 %). За рибогосподарськими орієнтирами найбільш проблемними є БСК5 (60,4 %), ХСК (42,9 %), сульфати (42,4 %), перманганатна окиснюваність (40,8 %), нітрити (31,5 %) та амонійний азот (18,8 %). Кластеризація 48 репрезентативних пунктів виділила органічно-кисневий профіль (43 пункти), мінералізаційно-сольовий профіль (3 пункти) та біогенний профіль (2 пункти). Найвищий нормативний індекс I6 за господарсько-побутовими орієнтирами характерний для нижньої частини Південного Бугу в районі Бузького лиману, р. Інгул у м. Миколаїв, а також верхніх ділянок Південного Бугу нижче м. Хмельницький. Наукова новизна полягає у поєднанні багаторічного басейнового профілювання з нормативною інтерпретацією частоти перевищень і індексним ранжуванням пунктів моніторингу. Практичне значення результатів полягає у визначенні пріоритетних ділянок для поглибленого контролю, уточнення програм моніторингу та планування водоохоронних заходів.

ІНФОРМАЦІЯ ПРО СТАТТЮ :

Рукопис надійшов
5 березня 2026

Отримано після рецензування
9 травня 2026

Затверджено до друку
25 травня 2026

Опубліковано онлайн
30 травня 2026

Ключові слова :

поверхневі води; Південний Буг; гідрохімічний профіль; державний моніторинг; органічне забруднення; біогенні речовини; мінералізація; ГДК; кластеризація; індекс забруднення.

https://doi.org/10.26565/2410-7360-2026-64-25

УДК 574.4-043.86-047.58

Еволюція уявлень та структурно-логічне моделювання екопростору міст

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АНОТАЦІЯ

Поглиблено уявлення про фундаментальні чинники функціонування сталого простору ойкумени (територія – країна – держава – мегаполіс – місто – столичний центр) та його головного елемента – еколюдини (безконфліктні та еластичні проєкти, оптимальне планування та управління, екзистенційні інґредієнти, безпека середовища, психофізіологічне здоров'я та самоорганізація). В площині розвитку теорії географії та екології розроблено наочно-уявні моделі, що віддзеркалюють проблематику сталого столичного міста як в аспекті традиційного трактування (потреби суперсистеми – оптимальне планування та управління – проєкт – населення – мінімум забруднення та оптимум споживання), так і з позицій чинників його безпеки та загроз (актуалізовано такі складові, як глибина історії та культури; природна, геополітична, соціально-політична стабільність; невразливість місцеположення; позитивна карма у зв'язці з їх антиподами). Звернено увагу до екзистенційних чинників сталості Життя, його цінності та унікальності. Поглиблено зміст понять «ризикована географія», «екопростір», «екомісто», «сталість», «карма території», «компромісні столиці» та розширено діапазон їх застосування. Фрагментарно «озвучено» ретроспективу еволюції уявлень щодо ідеальної організації суспільного простору та сталих екополісів. Систематизовано широкий масив міжнаукової та міждисциплінарної інформації, значну частку якої вперше залучено до аналізу предмет-об'єктної сутності викладеного матеріалу, що свідчить про суттєву диверсифікацію окресленого дослідницького кола. Крім того, об'єктивність і переконливість озвучених позицій підсилюється значним експедиційним екодосвідом авторів та їх безпосереднім тривалим контактом з видатними вітчизняними вченими – міждисциплінарниками і екологами. Констатовано, що, незважаючи на утопічність вирішення проблеми створення сталого простору і реалізації проєкту екомісто та еколюдини, цей теоретико-практичний обрій залишається надзвичайно привабливим. Дослідження тісно пов'язане із цілями сталого розвитку ООН, зокрема з ціллю 11 «Сталий розвиток міст та громад».

ІНФОРМАЦІЯ ПРО СТАТТЮ :

Рукопис надійшов
29 грудня 2025

Отримано після рецензування
26 квітня 2026

Затверджено до друку
25 травня 2026

Опубліковано онлайн
30 травня 2026

Ключові слова:

структурно-логічні моделі, сталий простір, столичні центри, екомісто, екоризики, еколюдина. екзистенційні чинники, парадигма, цілі сталого розвитку ООН.

Вступ

В XXI ст. на порядку денному стоїть реалізація моделі екологічно безпечного (стійкого) розвитку, основні принципи якого сформульовано та підтримано Світовими самітами 1992 р. (Ріо-де-Жанейро), 1997 р. (Нью-Йорк), 2002 р. (Йоганнесбург). Стійкий (сталий) розвиток забезпечує потреби сучасного покоління і не призводить до втрати майбутніми поколіннями можливості забезпечення власних потреб. Зазначимо, що поняття «стійкий» та «сталий» мають спільні риси, особливо в контексті сучасних концепцій розвитку, і часто вживаються як синоніми для перекладу англійського терміну «sustainable». Проте, як той, так і інший термін не повною мірою відбивають англомовний сенс «sustainable», який в більшості випадків тлумачення буквально означає «постійно підтримуваний» [49]. За останні 50 років частка міського

Як цитувати : Бейдик Олександр, Гладкий Олександр (2026). Еволюція уявлень та структурно-логічне моделювання екопростору міст. *Вісник Харківського національного університету імені В.Н. Каразіна Серія «Геологія. Географія. Екологія»*, (64), 331–341. https://doi.org/10.26565/2410-7360-2026-64-25

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населення Землі збільшилась з 36% до 56%, у 2050 р. вона складатиме близько 70%. Політика стримування зростання міського населення не спрацювала і люди продовжують обирати для постійного проживання міста в пошуку кращої освіти та більш високооплачуваної роботи або банально жити за чужий рахунок на пільгах і менталітеті міських (часто столичних) агломерацій. А ще півстоліття тому в тих же Сполучених Штатах відношення до села (прагнення жити в сільській місцевості) було протилежним, про що пише Дреппер [1]: «Молодь не цуралась сільського оточення і не прагнула в міста, щоб там скоріше нажитися». І далі: «… в нас немає міст, але в нас є вдосконалене сільське населення; воно виховане на самоті, вміє насолоджуватися благами життя витончено».

Предмет-об'єктною сутністю та метою публікації є поглиблення та оновлення уявлень про феномен сталого столичного центру та простір його контролю шляхом застосування важелів моделювання, систематизації, діалектичного (дедукція, індукція), ретроспективного, порівняльно-географічного аналізу. З іншого боку, головна сутність «сталості» відповідно до концепції сталого розвитку – обмежувальна, а саме «зберегти ресурси для майбутніх поколінь». Це стосується первинного змісту концепції, закріпленого у Ріо – 1992. В подальших же модифікаціях цієї концепції, а далі, вже «стратегії» (Йоганнесбург, Ріо+20) ресурси планети не те що не стали берегти для наступних поколінь, а й дозволили країнам третього світу (умовно країнам Півдня) підвищувати свій добробут за рахунок саме невідновних ресурсів. Відомий вітчизняний еколог М.А. Голубець висловився: «Без потужного надходження поживи, пального, електроенергії і води механізми (автомобілі, фабрики та ін.) міста перестали б працювати. Люди швидко загинули б від голоду, або покинули місто» [44]. Тобто, «сталість» столичного центру не просто забезпечується його паразитизмом по відношенню до свого сільського оточення, а й спричиняє руйнування навколишніх екосистем для задоволення столичних потреб. Лейтмотив публікації полягає в акцентованій спробі ще раз привернути увагу небайдужої спільноти до цінності та унікальності Життя, що швидкоплинно проходить в синтетичному або природному середовищі та екзистенційних чинників його сталості. Автори розуміють певну вразливість цієї позиції, адже саме життя не може існувати поза екосистемною організацією біосфери, – натомість ми майже не використовуємо терміни «екосистема», «урбоекосистема», але саме вони як філософські категорії могли би бути у сфері авторських інтересів. В протилежному випадку напрошується висновок про інтереси людини (столичного мешканця) в задоволенні її потреб. Тобто, екзистенція стосується не живих систем, за рахунок яких існують усі міста, а власне, людини (Homo Urbanicus), існування (to existence) якої і забезпечують природні екосистеми. Природно, що автори не мають на меті переконати будь-яку людину з елементарним логічним мисленням в тому, що лавиноподібне зростання міст сприяє розвитку екосистемних відносин у біосфері [45,46]. Зауважимо, що викладене в статті подається в порядку обговорення, і, хоча базується на об'єктивному авторському досвіді та адекватному сприйнятті природно- та суспільно-географічних явищ і процесів, не позбавлене присмаку упередженості та суб'єктивізму.

Матеріали та методи

Викладений матеріал ґрунтується на даних офіційних джерел, застосуванні об'єктивних методів, методик та технологій дослідження (індукція, інформаційні технології, моделювання, експедиційні, соціологічні, картографічні методи). В той же час, зазначимо ще раз, що твердження, позиції та викладений матеріал в цілому подаються в порядку обговорення і можуть сприйматися в достатньо широкому спектрі – від аксіоматичних до дискусійних (наприклад, слова німецького філософа Макса Штірнера (1806-1856), які він наводить в праці «Єдиний та його власність» (1845): «... земля належить тому хто спроможній її захопити, або не дозволить її відняти у себе. Тигр, який нападає на мене, правий, і я, вбиваючи тигра теж правий») [2]. Проблематика Міста, сталості простору, фрагментарному аналізу якої присвячена стаття, має міждисциплінарний характер (стик площин географії, архітектури та містобудування, філософії, соціології, геополітики, країнознавства) та віддзеркалена у монографіях, матеріалах конференцій, законодавчих актах, періодичних виданнях, дисертаційних дослідженнях, атласах, наукових статтях, проектно-планувальних розробках як вітчизняних, так і зарубіжних авторів [3-25,27-48,50-54]. При роботі над статтею було залучено ряд методів і підходів (аналіз і синтез, діалектичний, статистичний, картографічний, моделювання, соціологічний, порівняльно-географічний), а камеральна обробка матеріалів експедиційних досліджень та ін. інформації передбачала використання сучасних комп'ютерних технологій. Академік М. М. Амосов щодо принципової оцінки моделей зазначав: «Існує гарний термін для позначення структури, що відображає іншу структуру. Цей термін – модель. ... Модель відображає об'єкт не повністю, а зі спрощеннями та спотвореннями – в залежності від того, задля якої мети вона призначена і які є можливості для її побудови» [3]. Масив джерел, які містить відповідний перелік, свідчить про значну диверсифікацію аспектів, що характеризують

якість (в т.ч. сталість) площинного (держави) та/або точкового (столичні центри) простору. Останній може розглядались як комплексно, так і в розрізі його акцентованих чинників (екологічних, управлінських, суспільно-політичних, геополітичних, кармічних, психологічних, планувальних, демографічних).

Результати

Десятки років спілкування та наукових консультацій з видатними вченими – архітекторами, екологами (І. Д. Родічкін, В. І. Нудельман, Є. Н. Перцик, М. М. Дьомін, Т. Ф. Панченко, І. М. Седак, В. Й. Зарецький, Г. О. Білявський, В. Я. Шевчук, М. М. Мовчан), участь у творчій роботі колективів провідних містобудівельних інститутів України («Діпроміcто», «КиївНДіПІмістобудування», «Київпроєкт») є підґрунтям формування теоретико-практичної неупередженості та об'єктивності авторів даної публікації. Автори, не раз перебуваючи за кордоном (експедиційний метод), знайомились з організацією екопростору не тільки десятків європейських столиць, а й флагманів втілення концепції сталого розвитку в інших частинах світу – столичних центрах Південно-Східної Азії – містах Сінгапур, Куала-Лумпур, Путраджая (останні два міста, відповідно, історична та новостворена столиці Малайзії) та еколокаціях Африки – у м. Марракеш (парк Мажорель з віллою-ательє художника-орієнталіста Жака Мажореля, де пізніше мешкав та шукав натхнення видатний модельєр Ів Сен-Лоран).

Ретроспектива ідеального міста. В контексті фрагментарного аналізу рис. 1 «озвучимо» ретропогляд на видатних теоретиках та попередниках ідеї екопростору – держави, острова, поліса, на їх світоглядних роботах – Платона, Андрее, Мора, Бекона і Кампанелли. В «Утопії» Томаса Мора (1478–1535) наведено опис вигаданого острова з ідеальним суспільним устроєм. В утопічній новелі Френсіса Бекона (1561–1626), події якої відбуваються на о. Бенсалем, наука відіграє домінуючу роль, але червоною ниткою проходить ідея життя мешканців острова у злагоді з природою. В «Місті Сонця» Томмазо Кампанелли (1568–1639) йдеться про поселення, яке виникло навколо високого пагорба на о. Тапробану, де освітній процес відбувається під час прогулянок (аналогічно у В. О. Сухомлинського в «школі Радості») і передбачає прищеплення базових екологічних знань. В утопічному «Християнополісі» Іоганна Андрее (1586–1654) важливим державним завданням є забезпечення здоров'я громадян. Заради справедливості наведемо слова Льюїса Мамфорда (1895–1990) щодо ідей цього видатного богослова та письменника: «Андрее не один раз викличе у нас подив ідеями, що на 300 років випередили його час… Інші дві утопії, що написані в XVII ст. Ф. Беконом і Т. Кампанелою – лише посередні». Ці роботи є найбільш знаковими історичними творами, ідеї сталості та екологічності яких дотичні до книги Платона (427 до н. е. – 347 або 348 до н. е.) «Держава». В контексті викладеного вище зазначимо, що ці знакові праці були створені на початку модерну, умовною площиною відліку якого є «тридцятилітня війна» (1618-1648 рр.). Модерн, як історична епоха нового та новітнього часу, базується на трьох фундаментальних позиціях (цілях), «трьох китах»: 1) здобуття людиною безсмертя; 2) контроль за природою, «звільнення від її кайданів» та вихід за межі ойкумени: після освоєння географічного простору – колонізація космосу; 3) створення на Землі утопії – ідеального справедливого порядку. Всі ці цілі зазнали невдачі, адже в принципі не існує як безсмертя, так і життя у космосі, а проєкти «ідеального простору» є утопічними. Тим не менш, проблематика створення ідеальних конструктів і структур, сенсів і змістів залишається надзвичайно привабливою. Можливо, не всі погодяться з тим, що «всі ці цілі зазнали невдачі», бо знаходяться «в процесі» досягнення. Адже починаючи з промислової революції від дедуктивного методу Рене Декарта і аж до сьогоднішніх успіхів квантової фізики і космології йдуть пошуки шляхів вполювання «трьох китів», позначених авторами. Але, логічно, що найближче до безсмертя наблизились ті етноси, які знаходяться «найближче» до природи без міст – Індія, Пакистан, Ефіопія, Нігерія [47]. Другий кит, напевне, найбільш «впольований», про що свідчать небезрезультатні потуги, Маска, Безоса та інших. Зважаючи на те, що бажання «звільнитись від кайданів природи» стало головним підґрунтям войовничого антропоцентризму по відношенню до природи, найімовірніше вполювання третього кита якраз і буде залежати від докорінної зміни наголосів у другому завданні – від «звільнення від кайданів», тобто відмежовування до пошуку гармонії, тобто злиття.

Діагностика сталого міста: термінологія, моделі, чинники. Зважаючи на те, що важливим елементом транспарентності та змістовності викладеного матеріалу є його понятійно-термінологічний апарат, спробуємо окреслити його контур: екопростір (в ідеалі) – це територія такого змісту, наповнення та організації, де забезпечується комфортне існування та всебічний розвиток як людини, так і біоти (як бачимо, пріоритет тут надається людині; в той же час, в екосистемах людина виконує роль консумента, – при цьому в біосфері на продуцентів припадає 98,9% усього енергопотоку, на редуцентів – близько 1%, а серед консументів той 0,1% складають переважно інші популяції крім Homo Sapiens) [48]; на думку авторів, екоміста – локації єднання, взаємопроникнення при-

родних і антропогенних сил, ареали «здорового глузду», організації простору взаємодії та взаємоповаги двох тріад: рослини – тварини – люди + праця – побут – дозвілля. Фундаментальні властивості сталого міста – екоміста – еколюдини: самодостатність та невразливість. Стійкий – здатний протидіяти будь-якому тиску, а стійкість – умова збереження первісної структури. Стійке місто (та/або територія → країна → держава → їх коаліції та союзи) – просторово-часовий конструкт, сталість та стійкість якого забезпечують фундаментальні природні та суспільні чинники: збалансованість природного середовища та сейсмостійкість, історико-культурна глибина (кореневище території), підземна інфраструктура, геополітичне та суспільно-географічне положення, досвід функціонування у форматі тривалого часу та умовах радикальних суспільних інститутів. Стійке (замість «стійке» пропонується «Наближене до суті підтримуваного розвитку (sustainable)» столичне місто – це соціально-економічний та природно-географічний конструкт, що характеризується просторово-часовою, функціонально-статусною стабільністю і високим рейтингом впродовж тривалого періоду. Стійкість такої суспільно- та природно-географічної структури як столичний центр розглядається в двох аспектах: з позиції чинників безпеки цього конструкту (рис. 1) та в аспекті традиційного трактування (рис. 2). Розсипу міст – давніх і сучасних – притаманна різна стійкість: 1) одні міста, набуваючи піку свого розвитку, зникають назавжди (Мохенджо-Даро, Вавілон, Мачу-Пікчу, Петра, Карфаген); 2) інші – з глибоким історичним кореневищем, як фундаментальним чинником сталості, незважаючи на жахливу руйнацію «залишаються на плаву» (Алеппо і Дрезден, Мосул і Варшава); 3) треті – (умовно) з невисоким рівнем духовності та відносно молоді (Лос-Анджелес і Сан-Франциско, Торонто і Монреаль, Мельбурн і Сідней) зовні здаються благополучними. Стійкість столичного центру – це його постійний суспільний рейтинг і затребуваність як столиці (Брюссель, Лондон, Київ). В столичному центрі постійним залишається лише те населення, яке еластично вплетене і в його периметр, і в специфіку часу, і в аксіоми виживання. Населення як гетерогенний та частково передбачуваний конструкт, досягає свого перманентного життєвого оптимуму, розподіляючись у відповідних ієрархії та стратах. Стійке місто – історичний, суспільно-економічний, природно-ландшафтний і багатий благами конструкт, який пропонує населенню набір різноманітних опцій. Як індивіди, так і групи людей, створені для такого міста, вплітаються в його тканину та підтримують його стійкість. Сталі столичні міста та мегаполіси з глибинною історією, релігією та етнокультурою (Київ, Єрусалим, Багдад, Рим, Бейрут) мають більшу стійкість, ніж молоді (умовно) з невисоким рівнем духовності міста (Канберра, Оттава, Веллінгтон, Куала-Лумпур, Вашингтон). Політика суспільного розвитку міста періодично переглядається (відбувається певне перезавантаження) з урахуванням природних (катаклізми, стихійні явища) та суспільних (техногенні катастрофи, військові конфлікти, штучні епідемії) викликів.

Наочно-уявна модель (рис. 1) віддзеркалює суспільне прагнення щодо створення ідеального столичного центру.



Рис. 1. Структурно-логічна парадигма сталого міста (О.О. Бейдик, О.В. Гладкий, 2025)
Fig. 1. Structural-logical paradigm of a sustainable city (O.O. Beidyk, O.V. Hladkyi, 2025)

Принципова структурно-логічна парадигма сталого (наближеного до суті підтримуваного розвитку (sustainable)) міста має чотири блоки – 1): потреби світової спільноти в розвитку сталих просторів як альтернатива забрудненню довкілля, екологічній кризі та техногенному пресу на ойкумену; розвиток мережі екоінституцій та організація низки міжнародних самітів і конгресів, діяльність яких спрямована на гальмування та нейтралізацію поточного планетарного екоциду;

2)-3): не може існувати одного універсального проєкту сталого населення (селище, місто, столиця), адже розбіжності між територіями (ментальні, суспільно-економічні, природні, історичні) – категорія принципово стабільна. Уявлення про екологічність місцеположення та відчуття щастя, яке є складовою екоздоров'я людини (а людина – сутнісний центр сталого поселення), суттєво різняться простором ойкумени. «Будинки прерій» Френка Райта, який створив «органічну архітектуру» або споруди в стилі хай-тек, реалізовані проєкти Ле Корбюзьє (Шарль-Едуар Жаннере-Ґрі (1887 – 1965)) («сади на даху»; Чандігарх, Індія) та новаторські проєкти Нормана Фостера, в яких він прагнув реалізації ідеї олюднення виробничого простору (штаб-квартиру Bloomberg у 2017 р. було визнано найбільш екологічною спорудою в світі) відповідають ековимогам конкретного часу, певній території, визначеній функції, потребам людини. Наприклад, наші експедиції Південно-Східною Азією свідчать про високу екологічність поселень на палях на узбережжях оз. Тонлесап (Камбоджа) та р. Меконг (Лаос, В'єтнам), які демонструють повне злиття людини з довкіллям, та сельбищної зони м. Путраджая (нова адмінстолиця Малайзії), де втілені такі елементи екологічності як безпека існування, високий рівень задоволення суспільних потреб, наявність набору та зручності послуг;

4): останній, четвертий блок, може розглядатись не як другорядний, що залишився поза «трійкою призерів» і посів місце «за бронзою», а, навпаки, як рівний в цьому квартеті; природно, що людина → родина → населення може аналізуватись в оптиці десятків аспектів, основними з яких крізь призму екоздоров'я є безпека життєвого циклу (праця – побут – дозвілля), здоровий глузд і критичність мислення, екоповедінка в гетерогенному – синтетичному та природному – середовищі (сюди входять мінімізація відходів і аскетизм режиму споживання товарів і послуг); свого часу, задовго до поточної агресії, ми провели санкціоноване опитування громадської думки, яке включало десятки позицій, що знаходились в т.ч. у площині екології людини, стану її психіки в умовах столичних центрів і мегаполісів закордоння, яке засвідчило серед 4-х пар локацій найменшу тривожність при перебуванні в помешканнях Токіо та Осаки, а найбільшу – в помешканнях Сан-Паулу та Ріо-де-Жанейро.

Структурно-логічна модель (рис. 2) має 12 комірок, розташованих по колу, і за формою нагадує «колесо Сансари». В той же час модель містить ряд елементів, дотичних до Колеса, а її 12 категорій (в Колесі – 6 світів) є фундаментальними чинниками життя та діяльності знакових пазлів планетарного соціуму. Отже, «телеграфно», по дотичній пройдемо 12 елементів моделі:

1-7: шеренгу духовних і (умовно) з невисоким рівнем духовності держав демонструють наступні тандеми: Китай (IV –III тис. до н. е.) – США (1776), Індія (IV –III тис. до н. е.) – Австралія (1788), Іран (III тис. до н. е.) – Нова Зеландія (1769), яка останнім чином реалізує кроки, спрямовані на реставрацію та залучення до сучасної суспільно-політичної діяльності явищ і реалій первісно-глибинної історико-культурної та релігійної спадщини маорі;

2-8: як фрагментарний приклад, окреслимо 2 групи країн: 1) що позбавлені впливу Ель-Ніньо (глобальний кліматичний феномен Південної півкулі, який викликає різке підвищення температури, посуху, спалахи малярії, лихоманки) та не входять до зони Тихоокеанського вогняного кільця; 2) що розташовані в зоні впливу цих природних феноменів. Прояв природних сил, їх інтенсивність (екстенсивність) та комбінації є чинником сталості території, в т.ч. і столичної. У випадку несприятливої, загрозливої природної ситуації щодо столиці, її функції передають іншому місту – наявному або новоствореному. Наприклад, помітне просідання Джакарти (столиця Індонезії) внаслідок дії сейсмічних та кліматичних чинників примушує владу шукати більш безпечне місце для столичного центру країни;

3-9: фактично це оціночний погляд, спрямований на зовнішній – ближній або дальній периметр, на безпосереднє або опосередковане оточення країни, яке може бути дружнім, нейтральним, ворожим; до вирішальних чинників відносяться і географічне розташування, військово-політичні блоки, транспортні комунікації (групи держав-антиподів: Австралія, Австрія, Велика Британія, Нова Зеландія, США, Уругвай, Швейцарія – Вірменія, Грузія, Кіпр, Лівія, Сирія, Молдова, Україна); до групи геополітично нестабільних країн потрапили в першу чергу ті, що тимчасово втратили контроль за своєю суверенною територією;

4-10: фактично це оціночний погляд, спрямований на внутрішній периметр, стан справ та рівня турбулентності всередині держави; політична та економічна складові внутрішнього периметру, як і інші процеси та явища суспільного конструкту можуть перебувати в 6 станах:



Рис.2. Антиподність екзистенційних чинників функціонування сталого столичного міста (О.О. Бейдик, О.В. Гладкий, 2025) /
Fig. 2. Antipodes of existential factors of sustainable capital city functioning (O.O. Beidyk, O.V. Hladkyi, 2025)

умовно-нормальному, передконфліктному, конфліктному, передкризовому, кризовому, передкатастрофічному, катастрофічному (групи держав-антиподів принципово схожі з 3-9, крім них: Люксембург – Ізраїль, Домініканська Республіка – Гаїті, Малайзія – Бангладеш, Словенія – Боснія і Герцеговина);

5-11: невразливість (вразливість) місцеположення сталого столичного центру (реального в ідеалі або в перспективі) в першу чергу пов'язана з радіусом кола від столиці країни, яке проходить твердою поверхнею – чим радіус більший, тим більша невразливість місцеположення; столичні центри, розташовані на узбережжях морів і океанів характеризуються переважно вразливим місцеположенням (тандеми: Делі – Вашингтон, Пекін – Єрусалим, Мехіко – Рига, Улан-Батор – Вільнюс, Тегеран – Кишинів, Мадрид – Таллінн);

6-12: карма – наслідки суспільно-політичних подій, рішень, вчинків, дій, що сформували відповідний державно-історичний простір; адекватний зв'язок між рішеннями та діями державоформуючих сил та їх наслідками. Господнє благословення, спрямоване на людину – населення – місто – країну («Якщо Господь не будує дому, марно працюють над ним будівничі. Якщо Господь не збереже міста, марно пильнує охорона», Пс. 126 [26]. Гуманні та негуманні діяння держави віддзеркалені в її сучасній долі (позитивна карма – Греція, Ірак, Іран, Італія, Китай, М'янма, Франція, Японія, негативна карма – Австралія, Канада, Косово, США, Туреччина).

Зазначимо, що рамкова аналітика 1-12 позицій, що викладена у часовій прив'язці на кінець першої чверті XXI ст., стосується як умовно площинних структур (території держав), так і в першу чергу точкових структур – сталих (формуючих свою сталість) столичних центрів, а сталості та екологічності частіше дотичні малі та середні міста (публікації В. А. Поповкіна, О. О. Любищева, ряду вітчизняних і зару-

біжних урбаністів та екологів). Так, В. А. Поповкін (Гехтман) [25] пише про малі міста США як «райські куточки», де екологія «працює» на людину, а людина є складовою екосередовища, що виступає ознакою сталості поселення. Йому вторить Е. Вайнер: «Маленькі міста душевніші, ніж великі» [40].

Ще раз підкреслимо, що концепція сталого міста передбачає наявність збалансованого та функціонально нормального психофізіологічного стану його населення, позбавленого будь-яких екстрахів, екотривог і екофобій. Слід зазначити (як приклад), що з позицій сталості (екологічності) поселення ми оцінюємо приватні помешкання (одно-двоповерхові будинки) в США, Канаді, Австралії та ін., оточені «білими парканчиками», як вразливі, достатньо небезпечні для життя структури, на відміну від поширених на території найбільшої за площею країни (в недавньому минулому) «хрущовок» – добротних і безпечних цегляних п'ятиповерхівок. Модульні селища, які набули поширення в сучасній України з 2022 р., як реакція на хвилі переселенців і біженців, слід розглядати як тимчасове, вимушене контрекологічне щодо здоров'я людини явище. В той же час мільйони людей є прихильниками саме «приватної одноповерхової ідеології», що проводять все життя саме в таких вразливих щодо безпеки проживання помешканнях. Саме така конформна, ортодоксальна позиція часто призводить до конфліктів з владою, яка, реалізуючи різноманітні місто- та мостобудівні проєкти примушує людей залишати свої «намолені» помешкання.

В науково-практичній площині є приклади точкового, поодинокого вживання поняття «ризикована географія», але в іншому, на відміну від даної статті, контексті. Останній дотичний до явища «центр-периферія» і полягає в тому, що столичний центр, оточений колом з максимальним (для «однорідної» контрольованої цим центром території) радіусом умовно демонструє «безпечну географію» (Ер-Ріяд, Бразиліа, Додома, Мехіко, Анкара, Санта-Фе-Де-Богота, Астана, Мадрид). Прикордонне, децентралізоване положення столиць (Київ, Берлін, Бразавіль, Кіншаса) формально демонструє саме «ризиковану географію». Численні приморські та приокеанічні столиці держав теж входять до цієї категорії, адже можуть бути атаковані як природною стихією, так і зазнати руйнації від природно-техногенних чинників (наслідки вибуху у водному середовищі). Ми детально не розглядатимемо категорію «ризикована географія», адже колесо історії, як і коло долі постійно перебувають в русі і те, що позавчора було найбільшим успіхом, післязавтра стане найбільшою трагедією: війна між США та Великою Британією (1812-1814), військові конфлікти Китаю з СРСР (1969) та В'єтнамом (1979-1990), застосування США атомної зброї проти Японії (1945) позавчора перетворились на конструктивні, доброзичливі та партнерські відносини між цими країнами сьогодні – у форматі сучасної геополітичної ситуації. Аналогічні тренди можна відслідкувати або передбачити щодо інших типів простору – територій, країн, регіонів, мегаполісів. Отже, наведені приклади можуть трактуватись як «вікно Овертона», що має геополітичний, країнознавчий контекст.

Сталі столичні міста, оточені суверенним простором, – це пазли штучної тканини ойкумени. Сучасний світ (світопорядок) – це система важелів і противажелів, які знаходяться в полі постійної змагальності. Кожні кілька десятиліть (діапазон тут достатньо рваний) в світі відбувається кривава генеральна ревізія дії важелів-противажелів і визначається відповідність і статус ролей, які грають на світовій сцені країни та державні коаліції, їх реальній силі, перевірка на відповідність геополітичним і геоекономічним формі та змісту.

Пам'ять історії містить ряд прикладів, коли фундаментальні елементи столичного центру, їх внутрішні та зовнішні «логістичні анкери» трансформувались або не відповідали існуючим викликам, внаслідок чого статус і функції столиці передавались іншому місту і виникав новий столичний конструкт (Вашингтон у США, Найп'їдо у М'янмі, «компромісні столиці» - Канберра в Австралії, Оттава в Канаді). В світі існує близько 200 держав (193 – члени ООН та понад 200 учасників літніх Олімпіад), які мають відповідні столичні центри, рівень сталості та екологічності яких вельми строкатий та асиметричний. На купюрі національної валюти України номіналом 500 грн є напис: «Нерівна всім рівність. Ллються з різних трубок різні струмені в різні посудини". Так підписав свій авторський малюнок фонтана Григорій Сковорода. Пояснював, що фонтан уособлює Бога, амфори – живих істот і людей. Нескінченне безсмертне начало (Бог) наповнює всі амфори, цим вони рівні. Проте амфори різного розміру, як люди, що мають різні здібності, тому вони – одночасно нерівні [34]. Люди – це населення країни. Країни – всі різні та, водночас, всі рівні. Кожна держава контролює те, що «захопила або не дозволила відняти» (Макс Штірнер) [2]. Також різна суспільно-політична «вага», екологічність і сталість їх столиць. Столиці різні, але, водночас, рівні. Такий геополітичний контекст слів Григорія Сковороди.

Еколюдина в сталому місті. Актуальності заклику видатного географа М. М. Баранського про те, що не варто забувати про центральне положення в суспільній географії Людини ніхто не скасовував. Ядро сталого міста – поняття в т.ч. історико-біосоціальне (антропологічне), етно-релігійне в якому знакові

події пов'язані з викликами і зусиллями людини. Тривале існування стаціонарних індикаторів культурно-історичної та релігійної функцій (культових та/або культурно-історичних споруд) суттєво підсилює реальність та визнання (легітимність) цього ядра. В Лондоні ядром є Вестмінстерське абатство (з його безпрецедентним біосоціальним змістом), в Парижі – собор Нотр-Дам, в Києві – Києво-Печерська лавра та Софійський собор, в Пекіні – Заборонене місто, в Токіо – район Чійода (Тійода), в Єревані – Матенадаран, який є одним із найбільших світових сховищ рукописів і найбільшим сховищем давньовірменських рукописів.

Головним елементом сталого столичного міста є, в ідеалі, «еколюдина», організм якої був позбавлений впливу будь-яких фізичних (травми, поранення, каліцтво), психофізіологічних (вживання медикаментів, фармацевтичних препаратів, вакцинація), психічних (спадкові або ін. захворювання, стреси, психотравми) чинників, а тому може виступати своєрідним еталоном, лакмусом, мірою сприйняття та оцінки явищ і процесів, які її оточують. В ідеалі така еколюдина сприймає місто, в якому живе, як локацію щастя, постійно перебуваючи в ньому як в найоптимальнішому для себе оточенні, або повертаючись до нього після тимчасової перерви. Заради паритету зазначимо і те, що в реалії будь-яка людина може виступати мірою сприйняття та оцінки оточуючих її явищ і процесів – принаймні в межах відповідної соціальної групи. Таким чином, головний елемент екоміста, його константа – еколюдина, життя і діяльність якої природно вплетені в його гетерогенну тканину (виробничу, побутову, дозвіллєво-рекреаційну, комунікаційну, спортивно-оздоровчу, релігійну, творчу, родинну). Кант у Кенігсберзі, Памук у Стамбулі, Борхес у Буенос-Айресі, Фіцджеральд у Нью-Йорку, Діккенс і Дойл у Лондоні, Хемінгуей і Саган у Парижі – це відомі приклади достатньо щільного злиття цих суперечливих і непередбачуваних особистостей з міським організмом, демонстрація просторово-часової єдності урбосередовища та індивіду, коли саме альянс часткового і загального народжував неординарний та суспільно-цінний продукт – твори науки, літератури та мистецтва. Усвідомлюючи розхожу аксіому щодо того, що люди часто розуміють одне одного з точністю до навпаки, окреслимо вишиті червоними нитками слова: «до якого би прошарку не належала людина, який би не займала соціальний пазл, вона в ідеалі здатна бути та усвідомлювати себе щасливою». Статки, суспільний локус, психофізичний стан часто не є вирішальними чинниками, щоб усвідомлювати себе щасливим елементом екоміста. Часто асоціальні групи або окремі індивіди, люди з обмеженими можливостями на відміну від т.з. «успішних» відчувають себе більш затребуваними та наповненими як сенсом, так і змістом. Покликання людини в столичному місті – відчувати як себе, так і місто, слухати, чути, бачити ці конструкти, адекватно розуміти сигнали, які вони надсилають, для формування алгоритму раціональної поведінки, яка передбачає оптимальний розвиток і щасливе життя. В центрі столиці Іспанії – Мадриду – є бар «Чікоте», який у 1931 р. відкрив Ріко Чікоте, щоб, як свідчить напис на фасаді (якому майже 100 років), «змішувати напої життя і думки людей, щоб люди і напої жили у злагоді». Тут ключове слово – «злагода» адже еколюдина має бути у злагоді з природою та соціумом, в злагоді з працею, побутом і дозвіллям. Посилюючи конструкт психічного здоров'я людини, кожної особистості та адекватність її світосприйняття, нагадаємо дві аксіоми: 1) успіхи та невдачі людини залежать виключно від її власних рішень; 2) людина, яка вважає, що отримала від життя недостатньо, повинна усвідомити, що має більше, ніж заслуговує. Взагалі, треба вміти грати будь-якими картами, які тобі надала Доля.

Висновки

- в площині розвитку теорії географії запропоновано структурно-логічні моделі, що фрагментарно віддзеркалюють проблематику сталого столичного міста як з позицій чинників його безпеки та загроз, так і в площині традиційного трактування; сталість – постійна (як мінімум фрагментарно) властивість і характеристика простору; константа, дотична окремих елементів, що містять запропоновані моделі;
- поглиблено зміст понять «ризикована географія», «екопростір», «екоміcто», «карма території», «компромісні столиці» та розширено діапазон їх застосування;
- світоглядну сутність категорії «сталість» поглиблено шляхом акценту на її антропологічну складову;
- фрагментарно «озвучена» ретроспектива формування уявлень щодо ідеальної організації суспільного простору та розвиток сталих екополісів;
- з часом проблематика стійкості простору та сталості міста буде прогресувати, набуваючи все більшої актуальності;
- систематизовано широкий масив різнорідної інформації, значну частку якої вперше залучено до аналізу предмет-об'єктної сутності викладеного матеріалу, що свідчить про суттєву диверсифікацію окресленого дослідницького кола.

Внесок авторів: всі автори зробили рівний внесок у цю роботу
Конфлікт інтересів: автори повідомляють про відсутність конфлікту інтересів
Декларація про використання генеративного штучного інтелекту: Автори використовували інструменти генеративного штучного інтелекту (GenAI) для допоміжної роботи: ChatGPT було залучено для допомоги в оформленні списку джерел. Усі результати роботи з цими інструментами були ретельно контрольовані, перевірені та, за необхідності, відредаговані авторами. Автори несуть повну відповідальність за зміст та цілісність публікації.

Authors Contribution: All authors have contributed equally to this work
Conflict of Interest: The authors declare no conflict of interest

Declaration of use of generative artificial intelligence: The authors utilized generative artificial intelligence (GenAI) tools in a supportive capacity: ChatGPT was brought in to help with the references list. All outputs from these tools were carefully supervised, reviewed, and, where necessary, edited by the authors. The authors retain full responsibility for the content and integrity of the publication.

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Evolution of conception and structural-logical modelling of cities' ecospace

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ABSTRACT

Introduction. *The subject-object essence and purpose* of the publication consist in deeper analysis and updating ideas about the phenomenon of sustainable metropolitan centers and the space of their control. The mail topic of the publication consists in an emphasized attempt to draw the attention of the interested community to the value and uniqueness of Life, which is fleeting in a synthetic or natural environment once again, and also to draw the attention to the existential factors of its sustainability.
Methods. The proposed investigation is based on data received from official sources as well as based on objective methods, techniques and research technologies (induction, information technologies, modeling, expeditionary, sociological, cartographic methods) usage. A number of methods and approaches were involved during our investigation (analysis and synthesis, dialectical, statistical, mapping, modeling, sociological, comparative-geographic analysis).
Results. The understanding of fundamental factors of oikumena's sustainable space functioning as well as its main element - eco-people is disclosed. In the field of geography and ecology theory development visual and imaginative models have been discovered that reflect the issues of a sustainable capital city both in terms of traditional interpretation as well as in terms of its security and threat factors. The existential factors of the constancy of Life, its value and uniqueness are focused on. The meaning of the concepts of "risk geography", "eco-space", "eco-city", "sustainability", "karma of the territory" as well as "compromise capitals" has been proposed as well as the range of their application has been expanded. A retrospective of the evolution of ideas regarding the ideal organization of public space and sustainable ecopolises has been fragmentarily "vocalized". A wide array of interscientific and interdisciplinary information has been systematized. The research is closely connected with the UN Sustainable Development Goals, in particular with 11 Goal "Sustainable development of cities and communities."
Discussion. It is necessary to note, that the information proposed in the paper is presented in the order of discussion only. It is based on the author's objective experience and adequate perception of natural and socio-geographical phenomena and processes. It is not devoid of insularity and subjectivity.
Conclusion. structural-logical models that fragmentarily reflect the issues of sustainable capital city both from the standpoint of its security factors and threats as well as from traditional interpretation thinking are proposed in the frames of geographic theory development;
the essence of "risky geography", "eco-space", "eco-city", "karma of the territory", "compromise capitals" concepts is deepened as well as the range of their application is expanded;
the ideological essence of "sustainability" category is deepened by focusing on its anthropological component;
a retrospective of ideas about optimal organization of public space as well as about the development of sustainable eco-polices are fragmentarily proposed;
the issues of spatial sustainability and city sustainability will progress over time, becoming increasingly relevant nowadays.

ARTICLE INFO

Manuscript received
29 December 2025

Revised manuscript received
26 April 2026

Manuscript accepted
25 May 2026

Available online
30 May 2026

Keywords:

structural-logical models, sustainable space, metropolitan centers, eco-city, eco-human, eco-risks, existence factors, paradigm, UN Sustainable Development Goals.

In cites: Beidyk Oleksandr, Hladkyi Oleksandr (2026). Evolution of conception and structural-logical modelling of cities' ecospace. *Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology*, (64), 331–341. https://doi.org/10.26565/2410-7360-2026-64-25 [In Ukrainian]

https://doi.org/10.26565/2410-7360-2026-64-26

UDC 574.52

Natural and anthropogenic influence on biological objects in the Danube mouth area

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ABSTRACT

Problem stastment. Recently, throughout the world there has been increased interest in the study of natural objects that occupy a special place on the earth's surface – the estuaries of rivers and their constituent parts – deltas. The estuary area of the Danube, which belongs to the category of specific natural objects and occupies a special place on the European continent, is considered in this study. The modern anthropogenic load on this geographical object requires a scientifically based assessment of its state. One of the assessment indicators proposed is the meiofauna diversity of the estuarine region, which clearly responds to the variability of environmental conditions. The results of this study will contribute to a better understanding of the processes occurring in the coastal zone, which will make it possible to achieve Sustainable Development Goal #14 – Life Below Water, aimed at conserve and sustainably use the oceans, seas and marine resources for sustainable development.
Purpose. The object of research is the river mouth area. The subject is the variability of the characteristics of natural conditions and components of biological populations with the aim of searching and possibly establishing their patterns.
Methods. A systematic approach was chosen as a methodology, which is based on considering an object as a system – a set of interacting objects, associated processes of water dynamics, seasonal season's variability of sinoptic prcosessis, the intensity of development of biological objects, etc.
Results. The reaction of biological organisms, using the example of meiobenos, to anthropogenic impact in areas of dredging, dumping of bottom sediments, background water areas and the natural influence of river flow and seasonal temperature fluctuations is considered. It has been established that meiobenthos indicators experience significant fluctuations in density and biomass not only depending on the location of the study areas, but depend on the season of the year, so in the spring the average density during the study period of meiobenthos was 104897±15243.0 ind./m2. In summer, density indicators almost double, averaging 253077±87606.7 ind./m2. In autumn they decrease on average to 132155±4837.3 ind./m2.
Conclusion. Using the classification of ecological quality (EcoQ), based on the meiobenthic richness (S) variable, the studied water area falls into a status from poor (Poor) in the spring to satisfactory (Moderate) in the summer and autumn. The variability of the studied characteristics (total meiobenthic density) depending on temperature shows the coincidence of a pronounced maximum of meiobenthos development in the summer.

ARTICLE INFO

Manuscript received
20 February 2026

Revised manuscript received
26 April 2026

Manuscript accepted
25 May 2026

Available online
30 May 2026

Keywords:

Danube estuary, river run off, air temperature, water temperature, meiobenthos, SDG #14, ecological quality, coastal zone, Black Sea.

In cites: Berlinskyi Mykola, Kulakova Irina, Morozov Victor, Slizhe Mariia, El Hadri (2026). Youssef Natural and anthropogenic influence on biological objects in the Danube mouth area. *Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology*, 64), 342–353. https://doi.org/10.26565/2410-7360-2026-64-26



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Introduction

Recently, throughout the world there has been increased interest in the study of specific natural objects that occupy a special place on the earth's surface – the estuaries of rivers and their constituent parts – deltas. The economic use of the rich land, water and biological resources of river mouths is expanding by various sectors of the national economy gravitating towards them. This is, first of all, agriculture (grain farming and the production of vegetable and industrial crops on fertile and deltaic lands, especially in warm climates); river and sea water transport, using the favorable position of river mouths at the intersection of waterways from seas to the interior of continents and vice versa – from rivers to seas, and port construction, fisheries (river mouths are places of spawning, feeding and migration of many valuable species of fish). In addition, river mouths are used by hydropower (construction of tidal power plants), public utilities (water supply to large port and industrial centers and settlements located at river mouths), pulp industry (reed extraction and processing), recreation, tourism, hunting, etc. [1].

At the same time, it is obvious that the modern anthropogenic load on this geographical object requires a scientifically based assessment, conservation and sustainable development from the point of view of the World Heritage ecosystem. One of the criteria proposed is the meiobenthos of the estuarine region, which clearly responds to the variability of environmental conditions. In addition, it is important to clarify at the preliminary stage of research the priority of anthropogenic and natural influences. This thesis is proposed to be highlighted as the purpose of the study. The object of investigation is the branch region of the Danube delta, and the subject of investigation is the daily changes in the characteristics of the medium and components of the biological populations of the branch region of the Danube under the influx of anthropogenic and natural factors.

A specific ecological component of benthic communities is the meiobenthos (meiofauna), which consists of protist and metazoan organisms smaller than 0.5 mm but being retained on a 63 μm mesh [2]. Meiobenthic nematodes are the most diverse and numerically dominant metazoans among-in the marine environment [3-5]. Nematodes due to specific biological characteristics (high productivity, short life cycles) quickly respond to environmental changes by reducing species diversity, increasing abundance and decreasing biomass [6, 7]. Meiobenthos is also able to be the first of the zoobenthos to restore its populations [8-12]. Biological indicators are considered more significant for assessing environmental quality than with only one physicochemical or abiotic variables [13]. The Water Framework Directive (WFD, 2000/60 / EC) and the Marine Strategy Framework Directive (MSFD, 2008/56 / EC) established the concept of Ecological Quality status (EcoQ) as a way to assess the biological quality of aquatic habitats. EcoQ status is based on the composition of several biological elements and organisms, and among these, meiobenthos and nematode communities may be used as possible tools to determine the EcoQ of the marine sediments [14-20].

The bottom ecosystems of the Odessa Gulf, the Danube coastal zone and with Zhebriyanskaya Bay including, as the part of it, are experiencing strong anthropogenic impacts [21-24].

The formation of meiobenthos in this area can be influenced not only by the large natural variability along the estuarine gradient (for example, the type and dynamics of sediments, the availability of oxygen, temperature and flow rate), but also by anthropogenic impact (for example, dredging and dumping).

Research Methods

To solve the set goals and objectives, the following methods and approaches were used: a systematic approach, a synergetic approach, an expeditionary method and analytical research methods. A systematic approach, which is based on considering an object as a system – a set of interacting objects, associated processes of water dynamics, seasonal synoptic variability, the intensity of development of biological objects, etc. The generalized comprehensive definition of the river mouth area should reflect the location, features of natural conditions and the processes that form them. The environmental conditions and biota in the mouth area of the Danube, where hydraulic engineering work is being carried out at the mouth of the Bistry branch, in particular, dredging and dumping of extracted soil into a designated dumping area, are considered. A station where the environmental characteristics are a priori not subject to anthropogenic impact from hydraulic engineering construction during the current observation period from 2016 to 2021 was selected as background values later, research was not possible. The selection and sorting of data was carried out taking into account the availability of actual measurements and their optimization in general. An assessment of statistical significance was performed. In Figure 1 shows a diagram of the stations whose data were used in the work.

The area is divided into three conditional sites: directly in the sites of dredging (Bystry branch) (depths 3–7 m), dumping (storage of sediment)

(depths 8–13 m) and in water areas remote from dredging and dumping, which can be considered as background where the impact of dredging operations is presumably minimal (depths from 6 to 26 m).

It is impossible to give a comprehensive definition of the river mouth area from the standpoint of any one discipline as a complex geographical complex. To date, the functional role of river mouths in the global process of interaction between land and ocean waters has also been little studied. An analysis of the seasonal dynamics of the taxonomic composition, abundance and biomass of the meiobenthos complex in the research region under the influence of the operation of agricultural agriculture was carried out on material collected in different seasons for the period 2016-2021. A total of 117 meiobenthos samples were processed and analyzed.

For the collection of meiobenthos samples, a Petersen bottom grab with an opening area of 0.25 m^2 was used. At each station, depending on the type of substrate from the monolith brought by the grab, a quantitative sample was taken with a frame of 10x10 cm with a depth of 5 cm into the ground. Then the meiobenthos sample was washed through a system of benthic sieves with a mesh size of 1 mm, 0.250 mm, 0.100 mm. To capture the meiofauna, a nylon mill sieves with a mesh size of 64 μm was placed on the lower sieve. A clot of suspension with organisms from the sediment was sorted by flotation and transferred to a container, the sample volume was brought to 100 cm^3 with distilled water with the addition of 4% formalin and the "Rosa Bengal" dye. Under laboratory conditions, the entire sample was viewed under a binocular microscope in Bogorov's chamber. All groups of meiobenthos were quantified. The number of organisms was recalculated for the entire sample (100 cm^3) and for 1 m^2 of the bottom surface [25]. All groups of meiobenthos were quantified. Each sample contained from several hundred to several thousand meiobenthos organisms, i.e., it was suitable for further systematic processing.

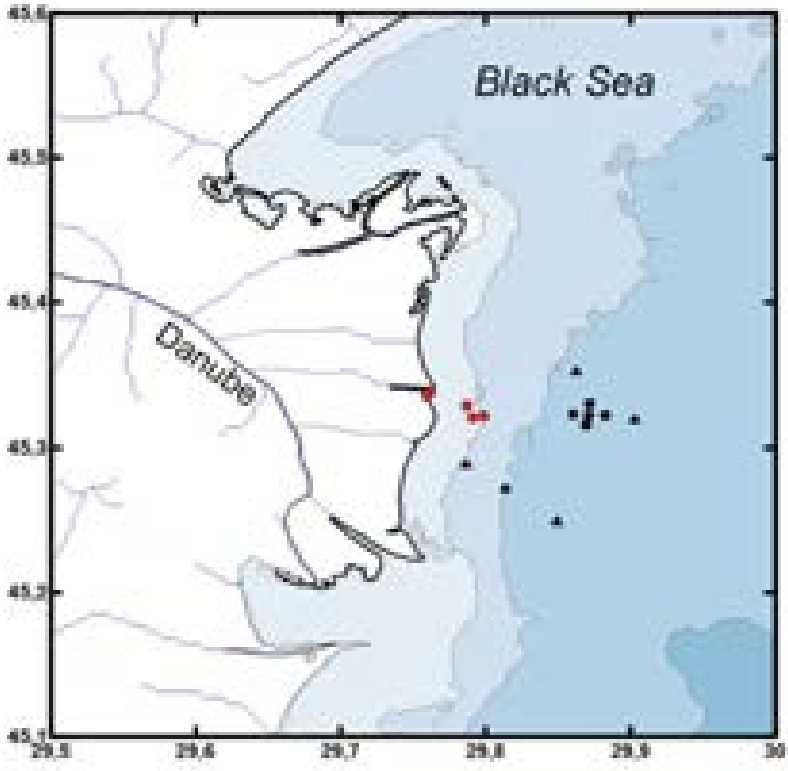


Fig. 1. Scheme of meiobenthos sampling stations in the Danube coastal area (northwestern part of the Black Sea): red circles – dredging stations, black circles – dumping stations, triangles – background stations

Table 1

Average air temperature and average water runoff in the study area

Month/Year	Air temperature, °C			Water flow values, m^3/s
	Average	Min	Max	Average
August, 2016	23.8	18.4	27.8	5480
November, 2016	7.2	-1.4	14.7	6230
August, 2017	23.9	16.9	29.4	3680
November, 2017	8.6	4.1	12.6	3680
August, 2018	25.0	23.4	27.5	4860
November, 2018	7.0	-4.3	15.6	3420
May, 2019	19.0	1.8	25.5	8160
August, 2020	24.2	21.4	27.3	4870
May, 2021	16.1	11.9	19.9	7100
October, 2021	12.5	7.6	14.9	3420

Table 2

Seasonal variability of air temperature and water runoff of the Danube

Seasons	Air temperature, °C				Water flow values, m³/s			
	Average	Standard error	Min	Max	Average	Standard error	Min	Max
Spring	17.6	1.5	16.1	19.0	7630	530.0	7100	8160
Summer	24.2	0.3	23.8	25.0	4428	449.2	3680	5480
Autumn	8.8	1.3	7.0	12.5	4188	683.6	3420	6230

The biomass of meiobenthos organisms was determined using the Chislenko nomograms [26].

Discussion Of Results

During the study period, data on air temperature in the estuary coastal area and the Danube runoff were used (Table 1). Seasonal variability data were selected depending on the beginning of the transition period. As the air temperature warmed up, the temperature of the surface layer of water began to increase in spring, decrease in autumn, and start of vertical circulation in winter.

The summer period does not have clearly defined values, since it is characterized by frequent surge fluctuations that affect the temperature. Therefore, it is proposed to consider the summer period from mid-June to mid-September with maximum temperatures in August (Table 2).

We considered the features of the distribution of quantitative characteristics of meiobenthos community in different seasons of the year in the area of construction of the shipping canal and dumping in comparison with the characteristics of small benthic invertebrate animals in water areas, which we consider as "background" and on which the influence of dredging is minimal. The meiobenthic community in the study area is represented by 13 high-ranking taxa: representatives of the permanent component (eumeiobenthos) – *Foraminifera, Nematoda*, *Harpacticoida*, *Ostracoda*, *Halacarida*, *Turbellaria*, *Gastrotriha*, *Kinorhyncha* and the temporary component (pseudomeobenthos) – *Oligochaeta*, *Polychaeta*, juvenile Bivalvia, Gastropoda, Balanus. The number of meiobenthos groups at stations varied from 2 to 8. In different seasons of the year, their number varied from 5 to 11, with their predominance in the summer.

Dredging area. Despite the dredging in the summer, the development of meiobenthos groups is observed, in contrast to the cold periods in spring and autumn. The influence of freshwater runoff variability, in particular its decrease in summer low water in contrast to temperature, is manifested in an increase in the development of meiobenthos groups and a reduction in meiobenthos groups in spring and autumn, which indicates the general dominance of natural processes of temperature and runoff development over anthropogenic processes, which (dredging) suppress the development of meiobenthos community (Fig. 2).

Five meiofaunal taxa (*Nematoda, Harpacticoida, Polychaeta, Oligochaeta and Bivalvia*) were found in the study area during spring. They dominated in density – Nematoda, made up 63% of the total meiobenthos, Harpacticoida (24.0%), as well as Polychaeta (14.0%), Oligochaeta made up only 1.0%. In terms of numbers, its permanent component (eumeiobenthos) significantly prevailed in the total meiobenthos, amounting to 87.0% of the total meiobenthos density (average density – 39963±32863.0 ind./m²; average biomass – 180.9±126 mg/m²) (Fig. 3).

In the summer, in the dredging area, an increase in the number of meiobenthos groups to seven was noted: *Nematoda, Harpacticoida, Ostracoda, Oligochaeta, Polychaeta, Bivalvia, Balanus*. However, the quantitative indicators of eumeiobenthos remained at the same level as in the spring, amounting to 91.0% of the total meiobenthos density (average density – 37531±17165.4 ind./m²; average biomass – 171.7±62.4 mg/m²). *Nematoda* dominated in density, 65% of the total meiobenthos, Harpacticoida accounted for 25.0%. The density of *Polychaeta* was (4.0%). Pseudomeobenthos accounted for 13.0% of the total meiobenthos density (average density – 3663±1054.3 ind./m²; average biomass – 157.0±40.5 mg/m²). In the autumn period, the number of meiofauna taxa will increase to eight, among them: *Foraminifera, Nematoda, Harpacticoida, Halacarida, Gastrotricha, Oligochaeta, Polychaeta and Bivalvia* were found in the study area. The density of Nematoda decreased to 22% of the total meiobenthos, Harpacticoida accounted for 27.0%, while the density of Polychaeta increased (26.0%), Oligochaeta accounted for 15.0%. Quantitative indicators of eumeiobenthos decreased significantly, amounting to 53.0% of the total meiobenthos density (average density – 5769±2068.2 ind./m²; average biomass – 40.7±24.6

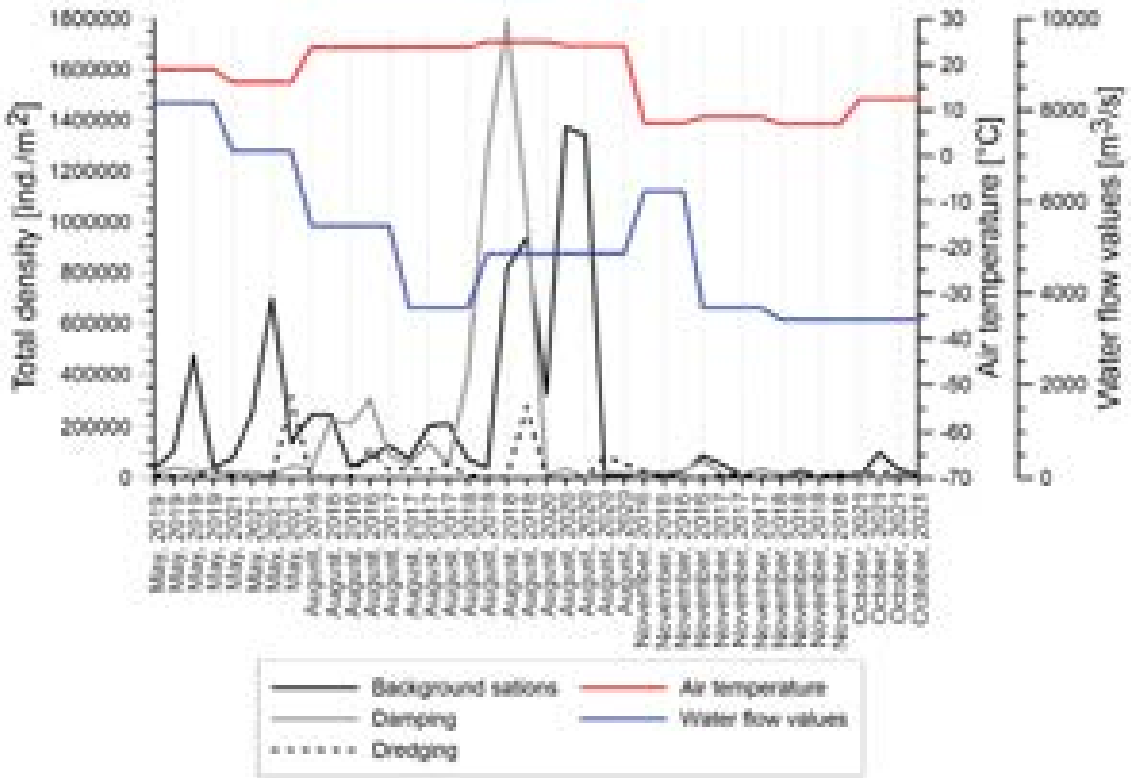


Fig. 2. The influence of environmental variability on the density (ind./m2) of meiobenthos on the Danube delta coastal area

mg/m^2). Pseudomeobenthos accounted for 47.0% of the total meiobenthos density (average density – 5215±1733.4 ind./m^2; average biomass – 327.5±115.5 mg/m^2).

Dumping area. From Figure 2 follows the dominance of the temperature component over the salinity component (Danube water runoff) in the dumping zone during the development of biological processes. At the same time, almost complete restoration of the benthic fauna often occurs, which confirms the feasibility of the alternate filling of the recommended sectors in the dumping proposed by the project developers.

Five meiofaunal taxa (*Nematoda, Harpacticoida, Turbellaria, Oligochaeta and Polychaeta*) were found in the study area during spring. In terms of numbers, its permanent component (eumeiobenthos) also significantly predominated in the general meiobenthos, amounting to 85.0% of the total meiobenthos density, but its quantitative indicators remained low, as in the dredging zone (average density - 22600±4167.6 ind./m^2; average biomass – 138.7±48.2 mg/m^2). The basis of the quantitative indicators of the entire meiobenthos were *Nematoda* (53%) and *Harpacticoida* (32%). Pseudomeobenthos accounted for 15.0% of the total meiobenthos density. (average density – 3888±1665.3 ind./m^2; average biomass – 334.8±100.5 mg/m^2). Among the temporary component, Polychaeta dominated in density from the total amount of meiobenthos (14.0%), Oligochaeta made up only 1.0% (Fig. 4).

In the summer, in the dumping area, an increase in the number of meiobenthos groups to eleven was noted: *Foraminifera, Nematoda, Harpacticoida,*



Fig. 3. Frequency (%) of average group density from the total meiobenthos density in the dredging area



Fig. 4. Frequency (%) of average group density from the total meiobenthos density in the dumping area

Ostracoda, Turbellaria, Kinorhyncha, Oligochaeta, Polychaeta, Bivalvia, Gastropoda, Balanus. Quantitative indicators of meiobenthos were an order of magnitude higher compared to spring. In terms of numbers, the meiobenthos was also significantly dominated by its permanent component (eumeiobenthos), amounting to 97.0% of the total meiobenthos density (average density – 355581±133814.2 ind./m^2; average biomass – 1825.1±913.1 mg/m^2). Nematoda dominated in density, accounting for 69% of the total meiobenthos, Harpacticoida – 25.0%. In the dumping area in the summer, as mentioned above, foraminifera, ostracods, turbillaria and gastrotrichs were recorded, but their quantitative indicators were insignificant. Pseudomeobenthos accounted for 3.0% of the total meiobenthos density and their indicators were not high compared to such eumeiobenthos, but higher than in the spring (average density – 11050±2903.2 ind./m^2; average biomass – 552.4 mg/m^2).

During the autumn dumping period, the number of meiofauna taxa decreases to seven, among them: Foraminifera, Nematoda, Harpacticoida, Oligochaeta, Polychaeta, Bivalvia and Balanus. The quantitative characteristics of the entire meiobenthos were low. As noted above, in the dredging area and at the dumping, there is a decrease in the share of eumeiobenthos in the total meiobenthos density and an increase in the share of pseudomeiobenthos representatives in the autumn period. Thus, the average density of eumeiobenthos decreased significantly, amounting to 62.0% of the total meiobenthos density (average density – 11067±2068.2 ind./m^2; average biomass – 17.1±7.7 mg/m^2).

Pseudomeobenthos accounted for 38% of the total meiobenthos density (average density – 6767±902.5 ind./m^2; average biomass – 343.4±50.9 mg/m^2). *Polychaeta* dominated in numbers from all meiobenthos (27%), *Oligochaeta* made up 6.0%. *Bivalvia* – 5%.

Background stations. From Figure 2 also follows the dominance of the temperature component over the salinity component (Danube water runoff) in the dumping zone during the development of biological processes. At the same time, almost complete restoration of the benthic fauna often occurs, which confirms the feasibility of the alternate filling of the recommended sectors in the dumping proposed by the project developers.

Eight meiofaunal taxa: *Nematoda, Harpacticoida, Turbellaria, Kinorhyncha, Oligochaeta, Polychaeta, Bivalvia and Balanus* were found in the study area during spring. The quantitative indicators of meiobenthos in this zone, in comparison with other study areas (dredging and dumping zones), were high. In terms of numbers, the meiobenthic community was also significantly dominated by its permanent



Fig. 5. Frequency (%) of average group density from the total meiobenthos density in the Background stations

component (eumeiobenthos), amounting to 95.0% of the total meiobenthos density (average density – 230071±95643.5 ind./m²; average biomass – 2323.8±1443.8 mg/m². The basis for the quantitative indicators of all meiobenthos were *Harpacticoida* (60%) and *Nematoda* (35%) (Fig. 5).

Pseudomeobenthos accounted for 5.0% of the total meiobenthos density (average density – 11957±4166, ind./m²; average biomass – 674.4±253.6 mg/m²). Among the temporary component, *Polychaeta* (3.0%) dominated in density from the total amount of meiobenthos; *Oligochaeta* made up only 1.0%.

In summer, at background stations, an increase in the number of meiobenthos groups to eleven was noted: *Foraminifera, Nematoda, Harpacticoida, Ostracoda, Turbellaria, Kinorhyncha, Oligochaeta, Polychaeta, Bivalvia, Gastropoda, Balanus*. In terms of numbers, its permanent component (eumeiobenthos) also significantly predominated in the total meiobenthos, amounting to 98.0% of the total meiobenthos density (average density – 354169±110057.7 ind./m²; average biomass – 899.2±381.9 mg/m²). Dominant in density of the total amount of meiobenthos were *Foraminifera* (51%), *Nematoda* (33%), *Harpacticoida* (13%). Pseudomeobenthos made up 3.0% of the total meiobenthos density and their indicators were not high compared to those of eumeiobenthos, and less by an order of magnitude than in the spring (average density ind./m² 8288±2562.1 ind./m²; average biomass – 445.5±126.9 mg/m²).

In the autumn period, the following meiofauna taxa were recorded at the background stations: *Foraminifera, Nematoda, Harpacticoida, Ostracoda, Halacarida, Oligochaeta, Polychaeta, Bivalvia, Gastropoda, Balanus*. A decrease in the proportion of eumeiobenthos in the total density of meiobenthos and an increase in the proportion of pseudomeiobenthos representatives in the autumn period were noted. The quantitative indicators of the entire meiobenthos were low and significantly lower compared to those in the summer. Thus, the average density of eumeiobenthos was 77.0% of the total meiobenthos density (average density – 23067±6927.6 ind./m²; average biomass – 60.8±10.0 mg/m²). Nematoda dominated in density from the total number of meiobenthos, amounting to 59%, Harpacticoida (9.0%), Foraminifera (8.0%). Pseudomeobenthos constituted 33% of the total meiobenthos density (average density – 6833±1451 ind./m²; average biomass – 368.7±74.5 mg/m²). The most abundant species of the total meiobenthos were Polychaeta (10%), Bivalvia – 6%, and Oligochaeta – 5.0%.

The heterogeneity of benthic conditions in this area is evidenced by the indicators of density and biomass of meiobenthos representatives, which varied greatly in the study areas under the influence of the marine shipping way operation to the Danube in different seasons in the period 2016-2021. A comparative analysis of the quantitative indicators of meiobenthos in the study area showed their minimum average values in the zone of construction of the shipping canal (dredging zone) and an increase at the dumping and especially at background stations (Fig. 6).

The average density of meiobenthos varied from 10167±2208.2 ind./m² in the autumn period of 2017. (min – 1000 ind./m², max – 28000 ind./m²) to 576583±156727.7 ind./m² in the summer of 2018 (min – 2000 ind./m² and max – 1798000 ind./m²). Average biomass indicators varied from 277.2±59.0 mg/m² in the autumn period of 2017. (min – 0.2 mg/m², max – 629.8 mg/m²) to 2931.9±1183.0 mg/m² (min – 0.4 mg/m², max – 15068.9 mg/m²).

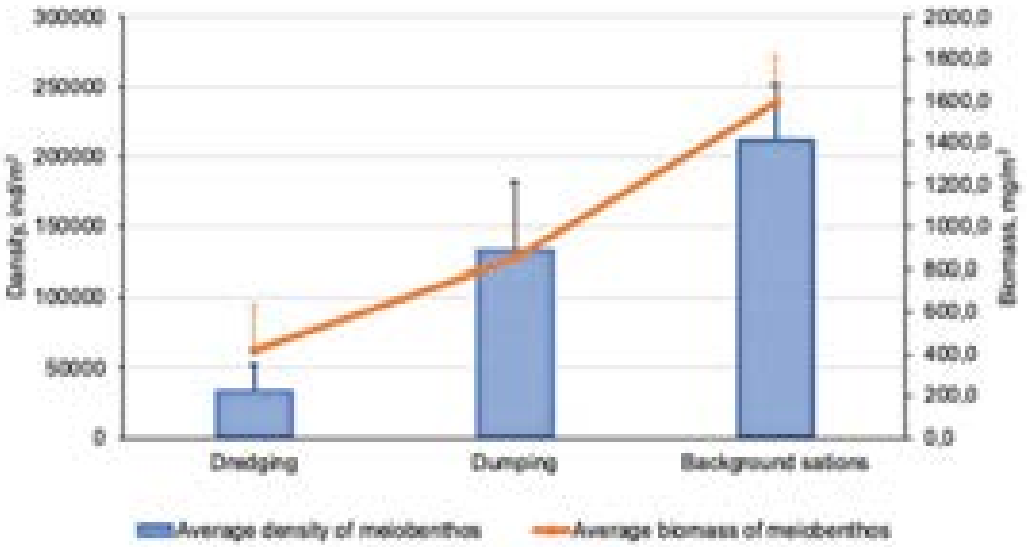


Fig. 6. Average density (ind./m2) and average biomass (mg/m2) of meiobenthos in the areas of the shipping way from the Black Sea to the Danube.

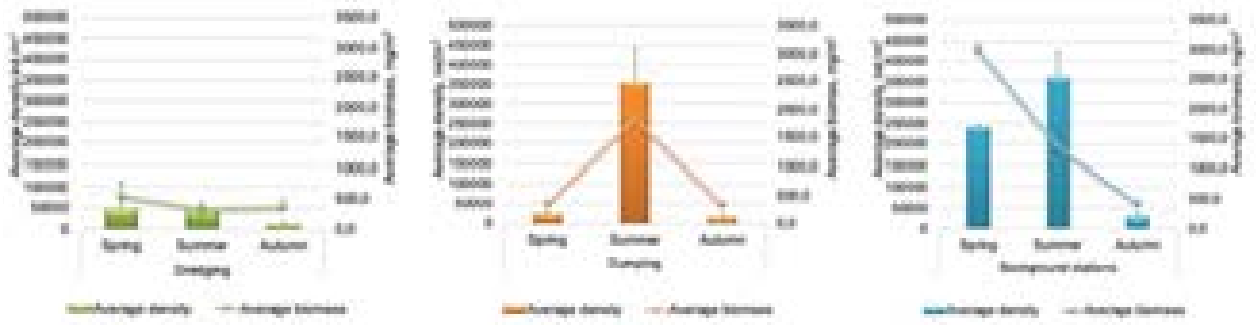


Fig. 7. Average density (ind./m^2) and average biomass (mg/m^2) of meiobenthos in the study areas at different seasons

In the dredging zone, the lowest average density of meiobmentos is recorded: from 46175±38385.5 ind./m^2 in spring and 41194±18082.4 ind./m^2 in summer to an almost threefold decrease in autumn at 10985±2810.4 ind./m^2. In the dumping zone, the highest indicators of the average density of meiobenthos depended in the summer period on 355581±133814.9 ind./m^2, in the spring and autumn periods its indicators were only 26488±4533.0 ind./m^2 and 17833±4134.5 ind./m^2, respectively. At background stations, the highest average density values are recorded in the spring, amounting to 242029±2810.4 ind./m^2, and especially in the summer (362457±110923.1 ind./m^2) (Fig. 7).

In autumn, the average density of meiobenthos was recorded an order of magnitude lower than previous seasons (29900±7567.0 ind./m^2). In spring, the average density of meiobenthos during the study period was 104897±15243.0 ind./m^2. In summer, density indicators almost double, averaging 253077±87606.7 ind./m^2. In autumn they decrease on average to 132155±4837.3 ind./m^2.

The quantitative and qualitative indicators of meiofauna in the Danube region are heterogeneous and depend on various hydrological factors (biotope structure, depth, oxygen). The water flow of the Danube also plays an important role. It is interesting to note that in low-water runoff years in the study area, an increase in the quantitative indicators of meiobenthos is observed compared to high-water years. Figure 8 shows that dependence of the maximum quantitative indicators of the meiobenthic community on freshwater runoff also persists for the spring – summer period. It is important to note that for the Danube the flood period is quite extended from April to July.

It is confirm the fact that the variability of salt and hydrological regimes leads to the fact that only organisms with great ecological plasticity can exist under these conditions. The zone of mixing of fresh and sea waters, which is characterized by a "minimum of species," in high-water years along the Danube flow shifts from the coast towards the sea, and in low-water years, on the contrary, this zone passes closer to the mouths, capturing some bays. The more stable the salt composition and the less influence of the Danube waters, the richer and more diverse the meiofauna.

Research has shown that complex changes are continuously occurring in the meiobenthic community, mainly related to seasonal temperature fluctuations. These fluctuations, according to [3], are predetermined by the seasonal cycles of reproduction of meiobenthic organisms. In addition, some authors indicate that seasonal changes in meiobenthic population density largely depend on seasonal changes in food distribution. Typically, high quantitative characteristics of meiobenthos are associated with the period of the year when there are optimal food sources and they are sufficient [27]. The structure of meiobenthos composition is greatly influenced by unforeseen (random) seasonal

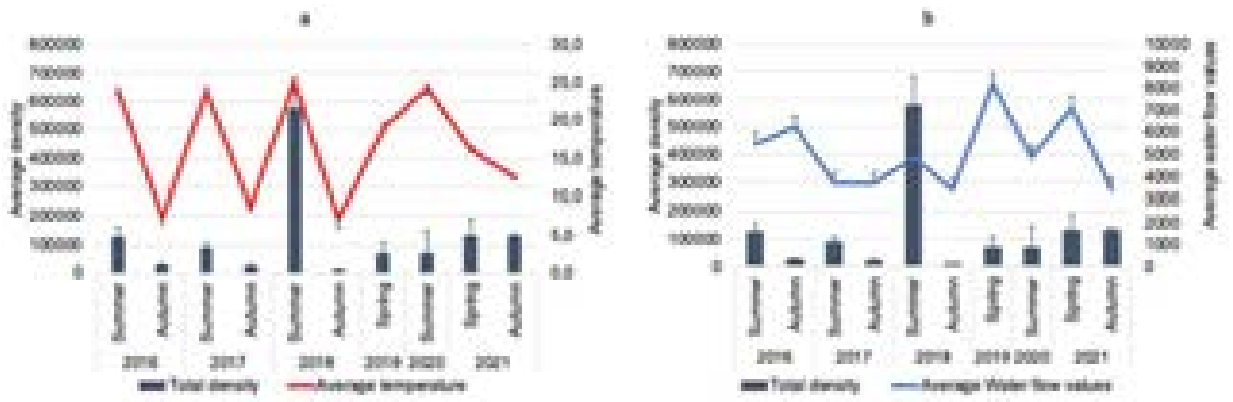


Fig. 8. Dependence of the total density (ind./m^2) of meiobenthos community on environmental conditions: (a) – air tempetature, °C; (b) – water flow values, m^3/s

Table 3

Thresholds of considered to evaluate the EcoQ of the study area according to Danovaro et al. [32]

Faunal parameters	High	Good	Moderate	Poor	Bad
Meiobenthic richness (S)	≥16	16<S<12	8<S<11	4<S<7	≤4

Table 4

Meiobenthic richness (S), calculated for different areas of the Danube estuary coastal zone in different periods of the year

Season	Spring	Summer	Autumn
Faunal parameters	Meiobenthic richness (S)		
Dradging	4	7	8
Dumping	5	11	7
Background stations	8	11	10

changes in environmental factors [28-30]. Also, the formation of meiobenthos in this area may be influenced not only by large natural variability along the estuarine gradient (e.g. sediment type and dynamics, oxygen availability, temperature and flow speed), but also by anthropogenic influences (e.g. dredging, soil dumping) [31].

The Water Framework Directive (WFD, 2000/60/EC) established the concept of environmental quality status (EcoQ) as a way of assessing the biological quality of aquatic environments. We attempted to assess the ecological status (EcoQ) of the study area based on the number (richness) of meiobenthic taxa, as proposed by Danovaro *et al.* [32], modified according to the WFD classes (Table 3).

In our studies, meiobenthos was characterized by 13 taxonomic groups. The value of meiobenthic richness (S) varied from 4 taxa in the dredging area to 11 taxa at the dumping and background stations (Table 4).

Using the classification of ecological quality (EcoQ), based on the variable meiobenthic richness (S), the studied water area falls into a status from poor (Poor) in the spring to moderate (Moderate) in the summer and autumn.

At the same time, almost complete restoration of the benthic fauna often occurs, which confirms the feasibility of the alternate filling of the recommended sectors in the dumping proposed by the project developers.

Conclusions

The variability of the studied characteristics (total meiobenthos density) depending on temperature shows the coincidence of a pronounced maximum of meiobenthos development in the summer.

The dependence of the maximum meiobenthos abundance on freshwater flow also persists for the spring-summer period. At the same time, almost complete restoration of the benthic fauna often occurs, which confirms the feasibility of the alternate filling of the recommended sectors in the dumping proposed by the project developers.

Using the classification of ecological quality (EcoQ), based on the meiobenthic richness variable (S), the studied water area falls into a status from poor (Poor) in the spring to moderate (Moderate) in the summer and autumn.

Внесок авторів: всі автори зробили рівний внесок у цю роботу

Конфлікт інтересів: автори повідомляють про відсутність конфлікту інтересів

Декларація про використання генеративного штучного інтелекту: Автори не використовували інструменти генеративного штучного інтелекту (GenAI) при написанні статті. Автори несуть повну відповідальність за зміст та цілісність публікації.

Подяка. Це дослідження підтримано проектом «Переосмислення COASTal landSCAPES із кліматичними втручаннями: системні рішення суша-море (COAST-SCAPES)». Автори висловлюють подяку Європейському виконавчому агентству з питань клімату, інфраструктури та навколишнього середовища (CINEA) за фінансову підтримку цього дослідження в рамках гранту 101213138.

Authors Contribution: All authors have contributed equally to this work

Conflict of Interest: The authors declare no conflict of interest

Declaration of use of generative artificial intelligence: The authors did not use generative artificial intelligence (GenAI) tools when writing the article. The authors retain full responsibility for the content and integrity of the publication.

Acknowledgments. This study is supported by 'Rethinking COASTal landSCAPES with climate-resilient interventions: systemic land-to-sea solutions (COAST-SCAPES)' project. The authors would like thank of the European Climate, Infrastructure and Environment Executive Agency (CINEA) for providing financial support of this research under Grant 101213138.

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ISSN 2410-7360 (Print)
ISSN 2411-3913 (Online)
Вісник Харківського національного університету імені В.Н. Каразіна Серія «Геологія. Географія. Екологія» 2026 64 С. 342–353
Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology 2026 64 342–353

Природний та антропогенний вплив на біологічні об'єкти в гирловій області Дунаю

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АНОТАЦІЯ

Останнім часом спостерігається підвищений інтерес до вивчення природних об'єктів, що займають особливе місце на земній поверхні – гирл річок та їх складових частин – дельт. В дослідженні розглядається естуарний район Дунаю, який належить до категорії специфічних природних об'єктів та займає особливе місце на Європейському континенті. Сучасне антропогенне навантаження на цей географічний об'єкт вимагає науково обґрунтованої оцінки його стану. Одним із запропонованих показників оцінки є різноманітність мейофауни естуарного регіону, яка чітко реагує на мінливість умов навколишнього середовища. Результати дослідження сприятимуть кращому розумінню процесів, які відбуваються в прибережній зоні, що дозволить досягти Цілі сталого розвитку №14 – Життя під водою, спрямованої на збереження та стале використання океанів, морів та морських ресурсів для сталого розвитку. Об'єктом дослідження є гирлова область річки. Предметом – мінливість показників природних умов та компоненотів біологічних популяцій з метою пошуку та можливого встановлення їх закономірностей. Як методику було обрано системний підхід, основу якого розгляд об'єкта як системи – сукупності взаємодіючих об'єктів, пов'язані процеси динаміки вод, сезонна синоптична мінливість, інтенсивність розвитку біологічних об'єктів та інших. Розглянуто реакцію біологічних організмів на прикладі мейобеносу на антропогенну дію в зонах днопоглиблення, дампінгу ґрунту, фонових акваторіях та природний вплив стоку річки та сезонних коливань температури. Встановлено, що показники мейобентосу зазнають значних коливань щільності та біомаси не тільки залежно від місця районів досліджень, але залежать від сезону року, тому навесні середня щільність за період дослідження мейобентосу склала 104897±15243,0 екз./м^2. Влітку показники щільності зростають майже вдвічі, склавши загалом 253077±87606,7 екз./м^2. Восени вони знижуються в середньому до 132155±4837,3 екз./м^2. Використовуючи класифікацію екологічної якості (EcoQ), засновану на змінній мейобентосу (Meiobenthic richness, S), досліджувана акваторія потрапляє в статус від бідного (Poor) у весняний період року до задовільного (Moderate) в літній і осінній періоди. Залежно від температури показує збіг яскраво вираженого максимуму розвитку мейобентосу у літній період.

ІНФОРМАЦІЯ ПРО СТАТТЮ :

Рукопис надійшов
20 лютого 2026

Отримано після рецензування
26 квітня 2026

Затверджено до друку
25 травня 2026

Опубліковано онлайн
30 травня 2026

Ключові слова:

естуарій Дунаю, річковий стік, температура повітря, температура води, мейобентос, ЦСР №14, екологічна оцінка, прибережна зона, Чорне море.

https://doi.org/10.26565/2410-7360-2026-64-27

UDC 556.531:504.45:504.064

Study of the influence of war on hydrochemical indicators surface waters of the Dnipro river within the boundaries of the city of Zaporizhya and Zaporizhya district

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ABSTRACT

Introduction. The Dnipro River is one of the largest river systems in Europe and a key source of surface water in Ukraine, which ensures the functioning of industrial, communal and agricultural water management complexes. Within Zaporizhzhia and Zaporizhzhia District, the river system is subject to the cumulative impact of many years of anthropogenic load caused by the high concentration of the metallurgical, energy, and chemical industries, as well as significant flow regulation due to the functioning of the cascade of Dnipro reservoirs. This forms a complex multicomponent hydrochemical regime with pronounced spatio-temporal heterogeneity of water quality indicators. At the same time, since 2022, the functioning of the Dnipro basin has been affected by an additional extreme factor - military actions, which significantly changed the structure and intensity of anthropogenic impacts on water ecosystems.
The purpose of article. The purpose of this study is a comprehensive assessment of the modern hydrochemical state of the surface waters of the Dnipro River within the city of Zaporizhzhia and the Zaporizhzhia district under conditions of increased anthropogenic and military influence, as well as the identification of the main patterns of spatio-temporal variability of key hydrochemical indicators.
Research methods. Methods of comparison, computer-based statistical data processing using correlation analysis of the results, as well as modeling and forecasting using regression analysis, were applied.
Research results. In order to achieve the stated aim of the study, we selected two monitoring points for the surface waters of the Dnipro River within the city of Zaporizhzhia and Zaporizhzhia District. The analysis was based on data from the Water Monitoring Laboratory of the Basin Water Resources Management of the Azov Rivers and covered the period from 2015 to 2026.
Conclusions. The paper presents the results of a comprehensive environmental assessment of the quality of surface waters of the Dnipro River within the city of Zaporizhzhia and Zaporizhzhia district. The analysis of hydrochemical parameters at the monitoring stations DVS-1 and the village of Bilenke for 2015–2026 indicates a generally relatively stable state of the aquatic environment, with a transition to an unstable regime after 2022 and especially in 2024–2025.

ARTICLE INFO

Manuscript received
20 March 2026

Revised manuscript received
3 May 2026

Manuscript accepted
25 May 2026

Available online
30 May 2026

Keywords:

surface waters, environmental assessment, anthropogenic load, water pollution, war impact, hydrochemical parameters, anthropogenic influence, military influence, Dnipro River, quality of surface waters.

In cites: Horoshkova Lidiia, Menshov Oleksandr, Maslov Denys, Korniichuk Yuliia, Horoshkov Stanislav (2026) Study of the influence of war on hydrochemical indicators surface waters of the Dnipro river within the boundaries of the city of Zaporizhya and Zaporizhya district. *Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology*, 64), 354–368. https://doi.org/10.26565/2410-7360-2026-64-27



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It is shown that at DVS-1 there is an increase in chemical oxygen demand (COD) without a corresponding rise in biochemical oxygen demand (BOD5), as well as an increase in suspended solids and mineral components (sulfates and chlorides). This indicates the input of hardly oxidizable and technogenic pollutants as a result of shelling of the city.
In the village of Bilenke, while a stable oxygen regime is maintained, a sharp increase in suspended solids, mainly of mineral origin, is recorded, as well as pulsed changes in biogenic elements due to intense upstream pollution (DVS-1).
The identified features are interpreted as a consequence of wartime impact, manifested through short-term intensive inputs of combustion and destruction products due to increased shelling intensity in Zaporizhzhia in 2025–2026, changes in the hydrological regime, and suppression of natural biogeochemical processes.

Introduction

The Dnipro River is one of the largest river systems in Europe and a key source of surface water in Ukraine, which ensures the functioning of industrial, communal and agricultural water management complexes. Within Zaporizhzhia and Zaporizhzhia District, the river system is subject to the cumulative impact of many years of anthropogenic load caused by the high concentration of the metallurgical, energy, and chemical industries, as well as significant flow regulation due to the functioning of the cascade of Dnipro reservoirs. This forms a complex multicomponent hydrochemical regime with pronounced spatio-temporal heterogeneity of water quality indicators. At the same time, since 2022, the functioning of the Dnipro basin has been affected by an additional extreme factor - military actions, which significantly changed the structure and intensity of anthropogenic impacts on water ecosystems.

Despite a significant number of studies devoted to the assessment of the quality of surface waters of the Dnipro, in modern conditions there is a need to apply complex approaches to the interpretation of changes in hydrochemical indicators, taking into account the simultaneous action of hydrodynamic, industrial and military factors. In this regard, the study of the hydrochemical parameters of the surface waters of the Dnipro River within the boundaries of the city of Zaporizhzhia and the Zaporizhzhia district under the conditions of war is an urgent scientific task aimed at establishing modern laws of the transformation of the water ecosystem, identifying the key factors of water quality changes, and clarifying the mechanisms of the formation of the hydrochemical regime under the conditions of increased anthropogenic pressure in the conditions of war.

The aim of this study. The purpose of this study is a comprehensive assessment of the modern hydrochemical state of the surface waters of the Dnipro River within the city of Zaporizhzhia and the Zaporizhzhia district under conditions of increased anthropogenic and military influence, as well as the identification of the main patterns of spatio-temporal variability of key hydrochemical indicators (in particular, suspended substances, biogenic elements, indicators of organic pollution and oxygen regime).

Within the scope of the goal, identification and quantification of changes in the hydrochemical characteristics of the water environment under the influence of extreme anthropogenic factors of military origin, establishment of their role in the transformation of the self-cleaning processes of the river system and disruption of the natural hydrochemical balance are envisaged.

Research methods. The analysis was based on data from the Water Monitoring Laboratory of the Basin Water Resources Management of the Azov Rivers and covered the period from 2015 to 2026 in the context of the following indicators: phosphate ions, ammonium ions, sulfate ions, chloride ions, nitrates, nitrites, BOD_5, suspended solids and dissolved oxygen.

Methods of comparison, computer-based statistical data processing using correlation analysis of the results, as well as modeling and forecasting using regression analysis, were applied.

Analysis of recent research and publications. The problem of anthropogenic impacts on the state of surface waters is a global one. That is why scientists pay considerable attention in their research both to the analysis of the hydrochemical regime of aquatic systems and to the search for ways to restore and stabilize aquatic ecosystems. The results of recent studies on surface waters in different countries are presented in articles [1–11].

This issue also remains in the focus of attention of researchers studying the condition of the surface waters of the Dnipro River and the sources of anthropogenic impacts that degrade its state [12-22].

The problem of surface water quality of the Dnipro River is one of the key issues in the ecological security system of Ukraine, since this river provides a significant part of the domestic and drinking water supply and functions under conditions of long-term anthropogenic load. The formation of the quality of Dnipro water is determined by a combination of natural-climatic, hydrological, hydrochemical and economic factors, and its assessment requires a comprehensive analysis of biogenic, organic, salt and oxygen indicators. A spatio-temporal approach to water quality assessment makes it possible to identify long-term trends in the deterioration of the state of water ecosystems, associated with the accumulation of

biogenic substances, heavy metals and the weakening of the river's ability to self-clean [12].

A significant contribution to the study of the Dnipro basin was made in the works devoted to the retrospective analysis of hydrochemical indicators and the modeling of the oxygen regime. It is shown that among the most informative indicators of the ecological state of river waters are the ratio between BOD_5 and dissolved oxygen, as well as the content of phosphates and ammonium, which characterize the organic and biogenic load [13-14]. For the Dnipro basin, a trend towards a steady deterioration of the ecological state under the influence of man-made factors has been established, and for forecasting changes in the oxygen regime, it is proposed to use models of the Streeter-Phelps type, which describe the balance between oxygen consumption during the oxidation of organic substances and its supply from the atmosphere. Such approaches create a theoretical basis for the analysis of ecological risks in water bodies, where the state of the oxygen regime directly reflects the level of disruption of self-cleaning processes [15].

A separate area of research is related to the assessment of the salinity of the surface waters of the Dnipro within the city of Zaporizhzhia. For the water intake areas of the city, it is shown that the sum of ions, chlorides and sulfates remain important indicators of anthropogenic transformation of the water environment. Ecological assessment by block of salinity revealed a relatively stable, but not background state of the waters, which is characterized as moderately polluted. This indicates the need to take into account not only biogenic and oxygen indicators, but also mineralization characteristics, since changes in the salt regime determine the ecological stability of the water body and the general hydrochemical stability of the river system in an urbanized environment [16].

With the beginning of a full-scale war, the problem of surface water quality gained new relevance. In modern works, it is emphasized that military operations affect aquatic ecosystems due to the fall into the water of explosion products, fuel and lubricants, fragments of equipment, the destruction of industrial and communal facilities, damage to sewage treatment plants, as well as due to changes in the structure of production and displacement of the population. For the Dnipro River within Zaporizhzhia, according to monitoring data, differences in the behavior of the main indicators of water quality before and after the start of the full-scale war were revealed, in particular for ammonium, BOD_5, dissolved oxygen, phosphates, sulfates and chlorides. The influence of war does not always manifest itself in the form of linear dependencies, since weather, hydrological, agrarian and man-made factors are simultaneously imposed on the state of water, but the war itself became a factor that significantly changed the nature of the dynamics of indicators and the structure of connections between them [17].

The further development of this direction is connected with the consideration not only of direct military pollution, but also of the long-term consequences of the destruction of hydrotechnical infrastructure. Research on the suspended sediments of the Dnipro and the Danube shows that the full-scale war caused a transformation of the hydrological and hydrochemical regime of the flow of large rivers, which, in turn, affects sedimentation and lithodynamic processes. The destruction of the Kakhovka Reservoir is considered as one of the largest factors of ecological restructuring of the river system, which changes the transport of suspended matter, the accumulation of pollutants and the conditions of long-term monitoring. In this regard, qualitative and quantitative characteristics of suspended sediments are beginning to be considered as an important addition to traditional hydrochemical indicators, as they reflect the accumulative effect of military and anthropogenic influence [18].

For the immediate Zaporizhzhia section of the Dnipro, modern research has formed a separate body of knowledge about the change in the hydrochemical regime under the influence of the war. In the works that analyzed the state of surface waters in the upper basin of the Dnipro HPP, the main attention was focused on the dynamics of BOD_5, dissolved oxygen, phosphates and ammonium. It is shown that the oxygen regime is one of the most sensitive indicators of changes in the river ecosystem, and the use of the Streeter-Phelps model makes it possible to estimate the balance between biochemical oxygen consumption and its atmospheric recovery. After the beginning of the war, and especially after the destruction of the Kakhovka HPP, the seasonal rhythms of the behavior of individual indicators changed, and the reduction of phosphate and ammonium concentrations at certain stages contributed to the improvement of self-cleaning conditions. At the same time, such a trend does not mean complete stabilization, since in the event of a return to the pre-war level of pollution, the risks of deterioration of water quality will increase again [6].

This issue is most systematically revealed in works where a comprehensive ecological assessment and forecasting of the state of surface waters of the Dnipro in Zaporizhzhia was carried out for the period 2013-2024. In these studies, it is emphasized that phosphates and ammonium have a pronounced seasonal and anthropogenic nature of fluctuations, sulfates are characterized by high

variability of natural and man-made origin, while chlorides are a more stable indicator of general mineralization. Special attention is paid to the violation of the seasonal dynamics of BOD_5 and dissolved oxygen after 2023, which is associated with the destruction of the Kakhovka dam and the change in the hydrological regime. At the same time, it was concluded that the partial ability of the river to self-recovery is preserved under the conditions of reducing the load of phosphates and ammonium [19].

The use of comparative methodological schemes tested on other river systems of Ukraine is also important for the development of research. In the works devoted to the Southern Bug, a combination of comparative analysis, correlation analysis, and regression forecasting was used to study the dynamics of phosphates, ammonium, sulfates, chlorides, BOD_5, and dissolved oxygen under wartime conditions. It is emphasized that the combination of these indicators makes it possible to simultaneously assess biogenic load, organic pollution, water mineralization and hypoxia risks. Methodologically, such works are important for the study of the Dnipro within Zaporizhzhia, as they demonstrate the possibility of integrating retrospective monitoring and predictive models into a single scheme for analyzing war-related changes in surface waters [20].

In the broader regional context, the study of bottom sediments and soils of the territories adjacent to the Dnipro, in particular the island of Khortytsia and the drained lakes formed after the destruction of the Kakhovka Reservoir, is also important for the Zaporizhzhya region. Significant excesses in the content of certain heavy metals, high values of magnetic susceptibility and complex relationships between lithogenic and technogenic components were revealed. Although such studies are not directly related to the hydrochemical indicators of the water column, they significantly expand the understanding of the general geoecological state of the Dnipro coastal-channel system in the Zaporizhzhia region and confirm that the military impact has a multi-component nature and is manifested not only in water, but also in bottom sediments and adjacent landscapes [21-22].

The existing mass of scientific works gives reason to assert that the study of the impact of the war on the hydrochemical indicators of the surface waters of the Dnipro River within the boundaries of the city of Zaporizhzhia and the Zaporizhzhia District is based on several complementary directions: spatio-temporal analysis of the quality of the Dnipro waters, modeling of the oxygen regime, ecological assessment of the salt composition, military-ecological analysis of monitoring series, the study of the consequences of the destruction of the Kakhovka Reservoir and forecasting of changes in aquatic ecosystems in the war and post-war periods

Research results. In order to achieve the stated aim of the study, we selected two monitoring points for the surface waters of the Dnipro River within the city of Zaporizhzhia and Zaporizhzhia District: 1) Dnipro River, 328 km, Zaporizhzhia, municipal drinking water intake (DVS No. 1) (47°81′80″ N, 35°10′00″ E); 2) Dnipro River, 0 km, drinking water intake of the Bilenke Municipal Enterprise, Bilenkivska Territorial Community, Zaporizhzhia District (47°62′04″ N, 35°05′10″ E).

The first monitoring point is located in the upper pool of the Dnipro Hydroelectric Power Station (Dnipro Reservoir), while the second is below the Dnipro Hydroelectric Power Station within the Kakhovka Reservoir (the channel of the Old Dnipro).

Fig. 1 shows the results of the analysis of changes in BOD_5, dissolved oxygen, COD, and suspended solids at monitoring point DVS-1 during 2015-2026.

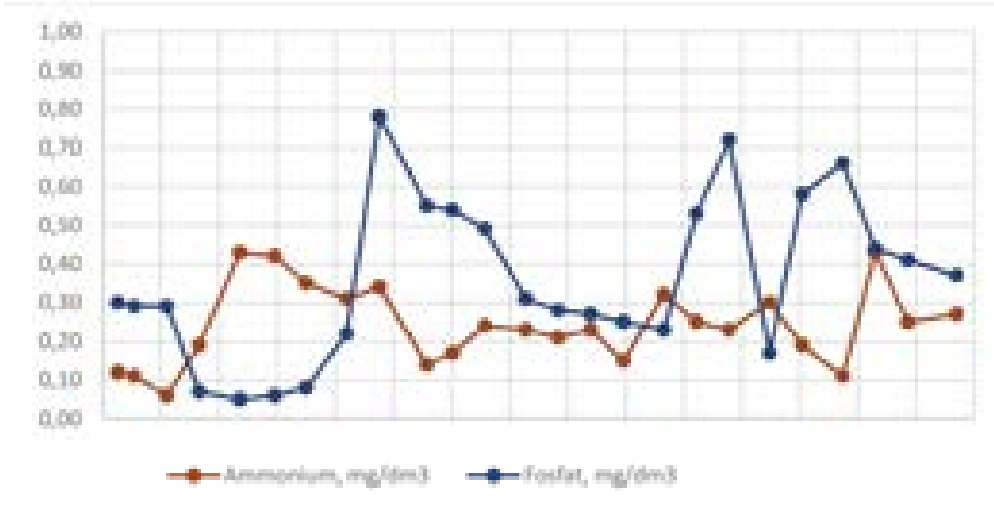


Fig. 1. Dynamics of changes in BOD5, dissolved oxygen, COD, and suspended solids at monitoring point DVS-1 during 2015-2026 (January)

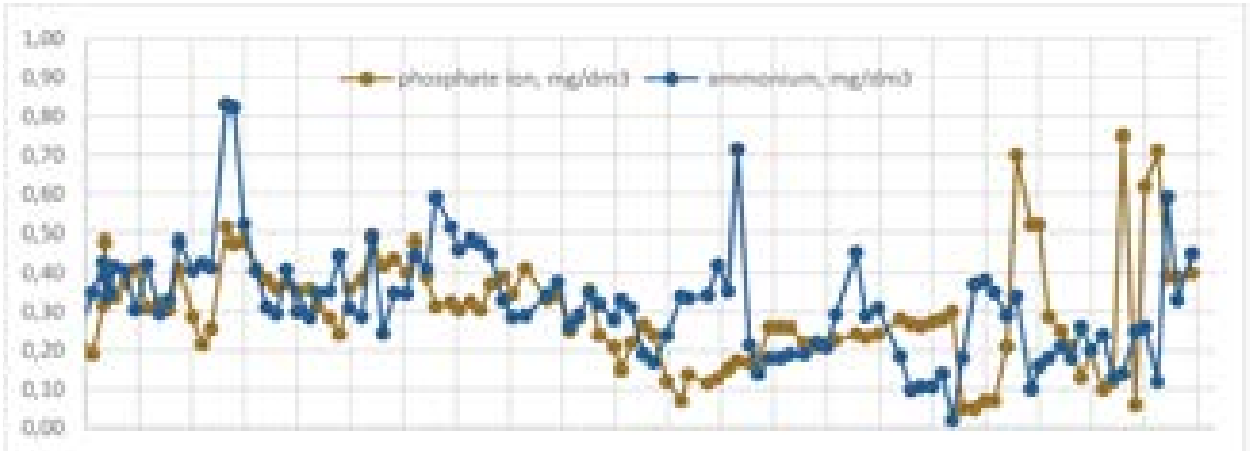


Fig. 2. Dynamics of changes in phosphate and ammonium ion content at monitoring point DVS-1 during 2017-2026 (January)

Analysis of the dynamics of changes in the value of BOD_5 shows that it varies in the range of 2.0-4.0 mgO_2/dm^3. The COD indicator constantly exceeds BOD_5 and is approximately in the range of 5.5-8.0 mgO_2/dm^3, which is expected, since it characterizes the total content of both biodegradable and oxidation-resistant organic substances. This may indicate the presence of hard-to-oxidize organic or certain inorganic components in surface waters.

The concentration of dissolved oxygen has a pronounced seasonal character: in the cold period it increases (up to 9-11 mgO_2/dm^3) due to the increased solubility of gases and a decrease in biological activity, while in the warm season it decreases (to 7-8 mgO_2/dm^3) due to the increase in water temperature and the activation of microbiological oxidation of organic matter.

As for COD, a significant increase in this indicator has been noted since July 2025 (with the exception of August and November). At the same time, the situation is atypical, because against the background of the increase in COD, the values of BOD_5 remain almost unchanged, only a slight summer increase is observed, which does not exceed the levels of previous years. The concentration of dissolved oxygen also maintains the trends characteristic of the previous period.

Another anomaly has been recorded since November 2025 - a sharp increase in the content of suspended solids from the traditional level of about 5 mg/dm^3 to 13 mg/dm^3, with further increases in the following months. It is worth noting that during the entire period of observation, no such deviations were detected, previously the maximum value was reached only once at the level of 6 mg/dm^3.

Fig. 2 shows the results of the analysis of changes in phosphate and ammonium ions at monitoring point DVS-1 during 2017-2026 (January).

Concentrations of ammonium NH_4+ vary in a fairly wide range (0.1-0.8 mg/dm^3). The most noticeable maxima are observed in 2018 (up to ~0.8 mg/dm^3) and in 2022 (about 0.7 mg/dm^3). After 2022, there is a certain decrease with periodic short-term increases. In 2024, minimum values are recorded (in places close to 0.1 mg/dm^3), after which moderate growth is again observed in 2025-2026.

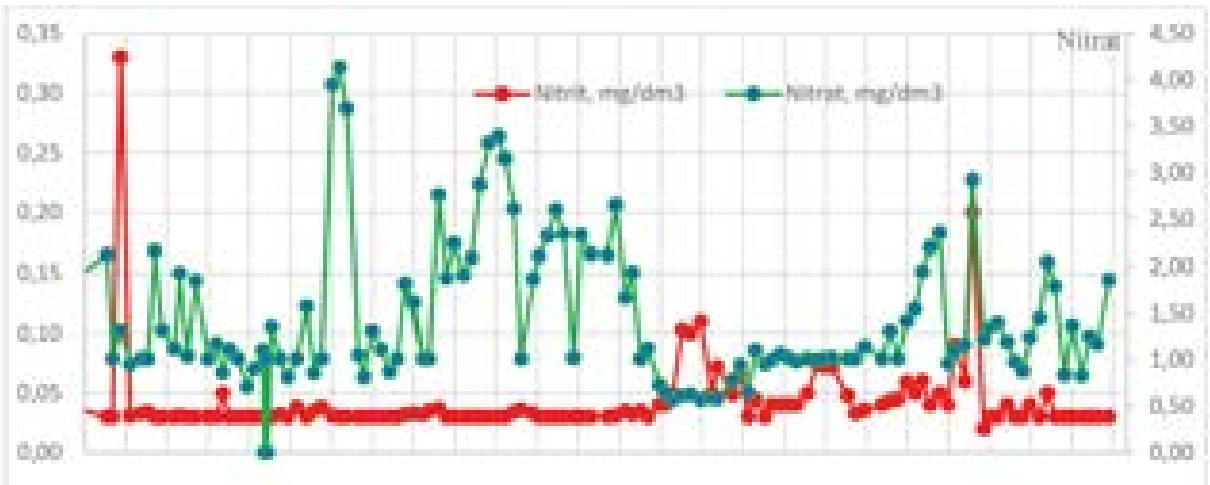


Fig. 3. Dynamics of changes in nitrite (NO_2^-) and nitrate (NO_3^-) concentrations in water for the period 2015-early 2026

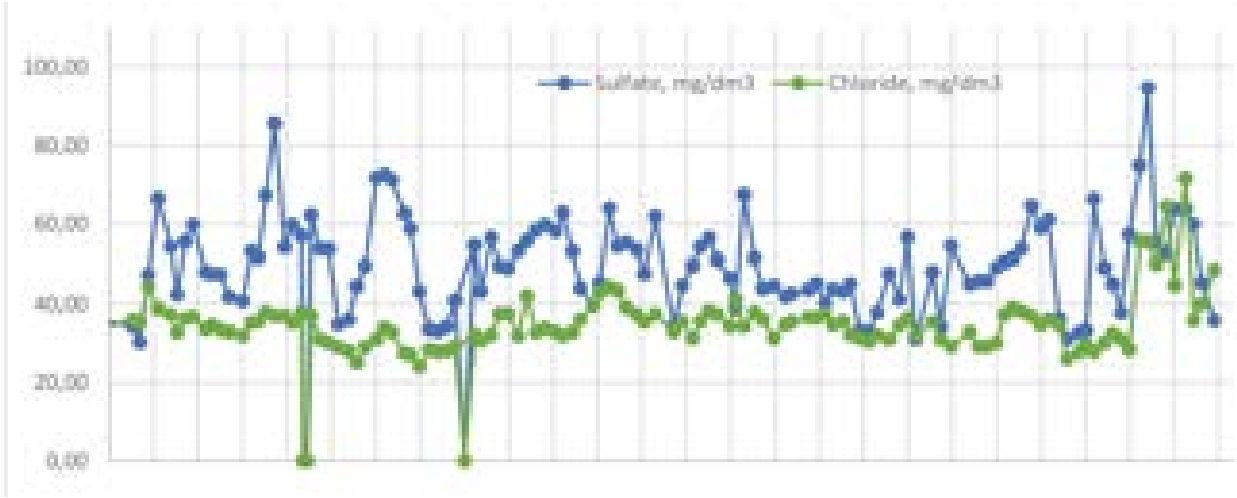


Fig. 4. Dynamics of changes in sulfate ion (SO_4^{2-}) and chloride ion (Cl^-) concentrations in surface waters for the period 2015-early 2026

The content of phosphate ions PO_4^{3-} also varies between 0.2-0.5 mg/dm³ in 2017-2023. Starting from 2024, more pronounced maxima appear - in 2024-2025, concentrations rise to 0.6-0.75 mg/dm³, which are the maximum values for the entire observation period. After the peak values, there are sharp declines, which indicates the instability of phosphate supply.

In 2024-2025, there is a certain asynchrony: phosphate content increases, while ammonium ions often remain at lower levels or fluctuate without sharp maxima at this time. The increase in ammonium may be related to the processes of decomposition of organic matter or additional pollution, while the increase in phosphate, especially in 2024-2025, may indicate an increase in anthropogenic influence.

Fig. 3 presents the temporal dynamics of nitrite (NO_2^-) and nitrate (NO_3^-) concentrations in water for the period 2015-early 2026.

The content of nitrites NO_2^- throughout the period remains mainly low and stable - about 0.02-0.05 mg/dm³. At the same time, sharp peaks that significantly exceed the background values are recorded. The most pronounced surge is observed at the beginning of the period (about 0.33 mg/dm³), as well as separate increases in 2021-2022 (up to ~0.1 mg/dm³) and in 2024 (up to ~0.2 mg/dm³). Such short-term growth may indicate episodic disturbances of nitrification processes or the arrival of fresh organic pollution.

Concentrations of nitrates NO_2^- vary in a much wider range (approximately 0.5-4.0 mg/dm³) and are characterized by more pronounced variability. The highest values were recorded in 2018 (more than 3-4 mg/dm³), as well as in 2019-2020 (about 2-3 mg/dm³). In 2021-2022, there is a decrease to minimum levels (~0.5-1.0 mg/dm³), after which in 2023-2024 there is a gradual increase with individual peaks (up to ~2-3 mg/dm³). In 2025-2026, the values remain moderate, with fluctuations within 1-2 mg/dm³.

Nitrites are an intermediate form in nitrification processes, so their concentrations are usually much lower than nitrates, which is confirmed by the given data.

The maxima of nitrite content, as a rule, do not coincide with the maximum values of nitrates, which indicates the short-term nature of NO_2^- accumulation and its rapid oxidation to NO_3^-.

During periods of increased nitrates (for example, 2018-2020), nitrites remain at a low level, which indicates the effective flow of nitrification processes.

The dynamics of nitrogen forms reflect the variability of biogeochemical processes in the water body. High concentrations of nitrates can be associated with both external input (flushing from the catchment, anthropogenic influence) and active nitrification. Episodic increases in nitrites indicate short-term disturbances in redox conditions or the arrival of fresh pollution. In general, the system is characterized by relative stability, but with periodic anomalies.

Fig. 4 presents the dynamics of sulfate ion (SO_4^{2-}) and chloride ion (Cl^-) concentrations in surface waters for the period 2015-early 2026.

Sulfate concentrations varied between 40-65 mg/dm³, with periodic increases. The most notable maxima are observed in 2017 (up to ~85 mg/dm³) and especially in 2025, where values reach maximum levels for the entire period (~90-95 mg/dm³). In 2018-2022, the dynamics are relatively stable, although fluctuations of average amplitude persist. After 2023, there is an upward trend with sharp short-term spikes.

The chloride content is more stable over a long period of time and is usually in the range of 30-40 mg/dm³. In 2015-2023, minor fluctuations are observed without sharp anomalies. Starting from 2024, a tendency to increase concentrations is noted, and in 2025, sharp peaks (up to ~60-70 mg/dm³) are recorded, which are atypical for the previous period.

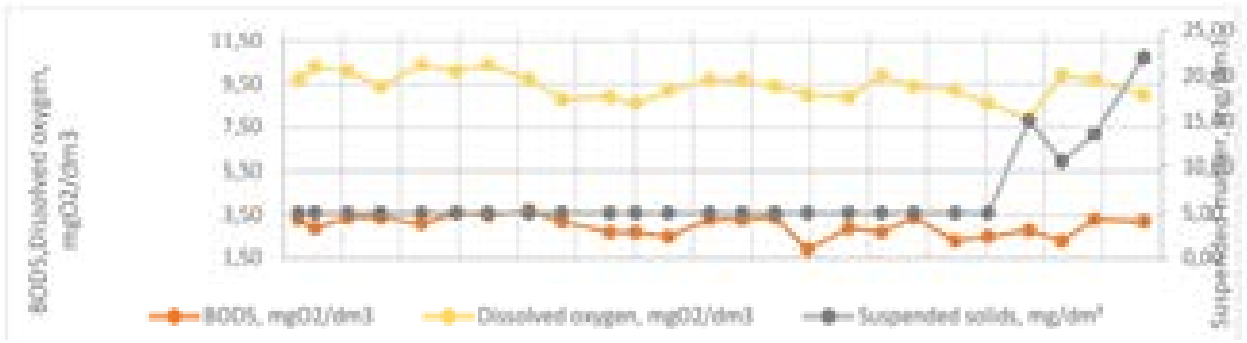


Fig. 5. Dynamics of changes in BOD_5, dissolved oxygen, and suspended solids from January 2024 to January 2026 at the monitoring point - the drinking water intake in the village of Bilenke

During the entire period, the content of sulfates was greater than the content of chlorides. Sulfates had a larger amplitude of oscillations and a more pronounced reaction to changing conditions. In 2025, there is a simultaneous increase in both indicators, which may indicate a common source of income or a change in the hydrochemical regime.

The dynamics of sulfates and chlorides reflects both natural processes (mineralization of water, hydrological conditions) and possible anthropogenic influence. A sharp increase in the content of both ions in 2025, especially after a long period of relative stability, may indicate an increase in man-made load.

Fig. 5 shows the dynamics of changes in BOD_5, dissolved oxygen, and suspended solids from January 2024 to March 2026 at the monitoring point – the drinking water intake in the village of Bilenke.

Throughout the studied period, the BOD_5 concentration fluctuates between 2.0 and 3.5 mg O_2/dm³, which indicates a moderate level of organic pollution. In 2024, this indicator is relatively stable with minor fluctuations, with a short-term decrease in early 2025, followed by a gradual increase in the second half of 2025 to peak values at the end of the year. The content of dissolved oxygen throughout the period remains quite high and varies between 8.5-10.5 mg O_2/dm³. In 2024, the values are consistently high, in the first half of 2025 there is a slight decrease, and at the end of 2025 - an increase again, which in general indicates favorable conditions of the oxygen regime of the water environment.

The most pronounced changes are characteristic of suspended solids: during 2024 and most of 2025, their concentration remains almost constant at the level of about 4-5 mg/dm³, but from the fall of 2025, there was a sudden increase to maximum values of more than 20 mg/dm³ at the end of the studied period. Such dynamics may indicate the influence of short-term but intense factors, in particular hydrological processes or increased anthropogenic load. In general, there is a stable organic and oxygen water regime against the background of a sharp and abnormal change in the content of suspended matter at the end of the observation period.

Fig. 6 shows the change in ammonium and phosphate ion concentrations in surface waters from January 2024 to January 2026.

The ammonium content fluctuates within the range of approximately 0.05-0.45 mg/dm³

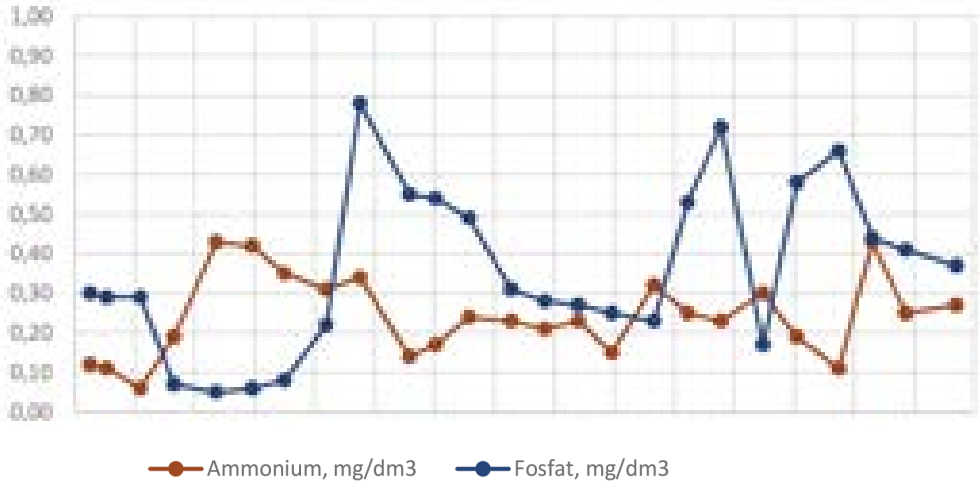


Fig. 6. Dynamics of changes in ammonium and phosphate ion concentrations in surface waters from January 2024 to January 2026

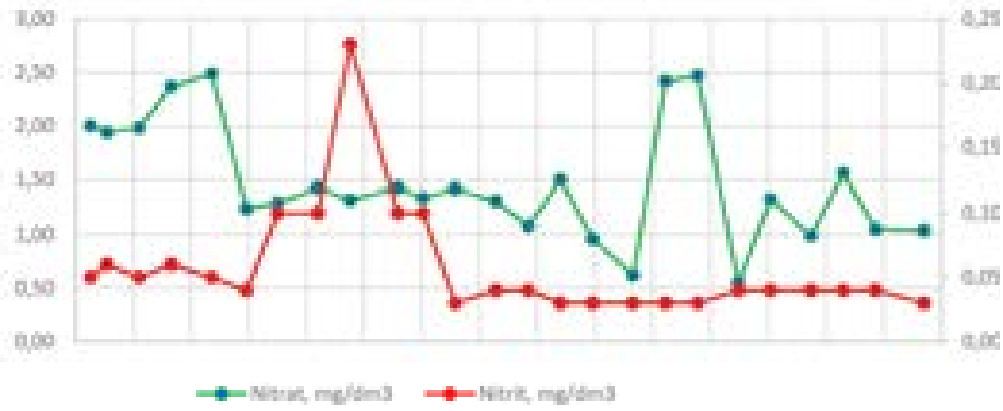


Fig. 7. Dynamics of changes in nitrate and nitrite concentrations in surface waters in the period from January 2024 to January 2026

throughout the entire time. At the beginning of 2024, its values are relatively low, after which there is an increase in the spring and early summer to a maximum of about 0.4-0.43 mg/dm³. In the second half of 2024, the concentration of ammonium decreases and continues to be mainly at a moderate level with minor fluctuations. Throughout 2025, there were ups and downs, with local increases in the middle and end of the year, and at the beginning of 2026, the values stabilize at around 0.25-0.27 mg/dm³.

The concentration of phosphates changes more sharply and in a wider range - from 0.05 to 0.8 mg/dm³. At the beginning of 2024, the content of phosphates was at the level of 0.3 mg/dm³, in the spring there is a decrease to minimum values, after which a sharp peak of almost 0.8 mg/dm³ is recorded in September 2024. In the future, the values gradually decrease at the end of 2024 - the beginning of 2025, but in the summer and autumn of 2025 significant fluctuations are again observed with several pronounced rises above 0.6-0.7 mg/dm³. In general, the graph shows more stable dynamics of ammonium and much more variable dynamics of phosphate content, which may indicate the periodic influence of certain natural or anthropogenic factors on the phosphate regime of water.

Fig. 7 presents the dynamics of nitrate and nitrite concentrations in surface waters in the period from January 2024 to January 2026.

During the entire period, the nitrate content is characterized by moderate variability with fluctuations in the range from 1.0 to 2.5 mg/dm³. In early 2024, nitrate levels are relatively stable and fairly high, increasing to local maxima in the spring, followed by a marked decline in the early summer. In the second half of 2024, the concentration of nitrates fluctuates around the average values. In the spring of 2025, a decrease to the minimum values for the studied period is noted, while in the summer months a sharp increase of nitrates to a level of more than 2.4 mg/dm³ is recorded. In the future, the nitrate content will decrease and at the end of 2025 - at the beginning of 2026 will stabilize at the level of about 1.0-1.1 mg/dm³.

The concentration of nitrites in the water during the entire period is significantly lower, but it is characterized by sharper and more uneven dynamics. In the first half of 2024, nitrite values mostly do not exceed 0.07 mg/dm³, after which there is a pronounced sharp peak in August-September 2024 with an increase to almost 0.25 mg/dm³. After that, the concentration decreases rapidly and during most of 2025 is kept at a relatively low and stable level, around 0.03-0.05 mg/dm³, with minor fluctuations. At the end of 2025, no significant increases in nitrites are observed, and at the beginning of 2026, the values remain low. In general, the obtained data indicate a more stable nitrate water regime and episodic, short-term spikes in nitrite content, which may be associated with temporary disturbances of nitrification processes or external input of nitrogen-containing compounds.

Fig. 8 shows the change in sulfate and chloride concentrations in water for the period from January 2024 to January 2026.

The content of sulfates during the entire period is higher than the concentration of chlorides and is characterized by noticeable variability. At the beginning of 2024, sulfate values are around 55-60 mg/dm³, with a gradual increase to 65-67 mg/dm³ in the spring and early summer, followed by a sharp drop to around 35-40 mg/dm³ in September. At the end of 2024, the concentration of sulfates increases sharply to a local maximum of about 70 mg/dm³, and at the beginning of 2025 it decreases again. In mid-2025, the highest level for the entire monitoring period is recorded — more than 80 mg/dm³, after which the values gradually decrease and approach 40 mg/dm³ by the beginning of 2026. Chloride concentration varies in a narrower range - from 25 to 65 mg/dm³. In 2024, the chloride content was in the range of 30-37 mg/dm³

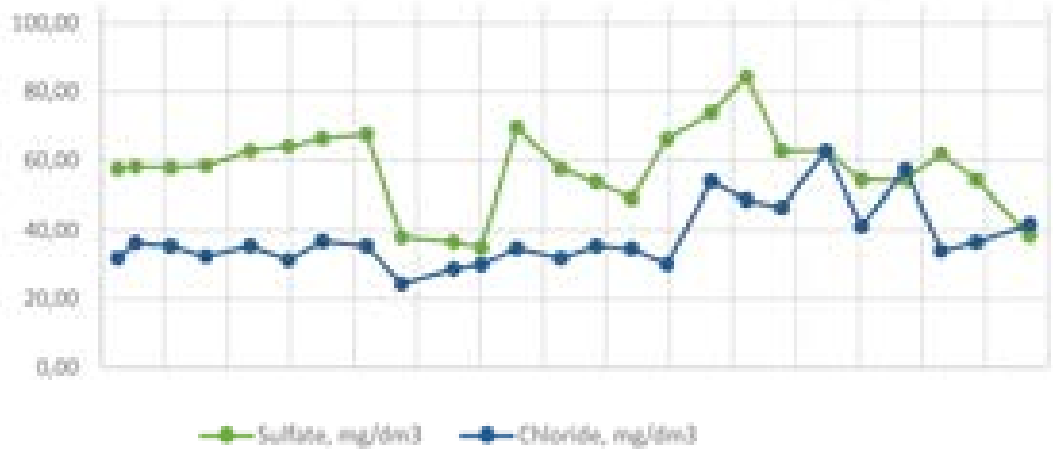


Fig. 8. Dynamics of changes in sulfate and chloride concentrations in water for the period from January 2024 to January 2026

with a short-term decrease to minimum values in autumn. In 2025, an increase is observed in the spring, and a maximum of about 60-65 mg/dm^3 was recorded in the summer. At the end of 2025, the concentration of chlorides decreases, and at the beginning of 2026, it stabilizes at the level of about 40 mg/dm^3.

A comparative analysis of hydrochemical indicators of surface waters at monitoring points DVS-1 (the upper pool of Dnipro HPP in the city of Zaporizhzhia) and the village of Bilenke, located downstream, indicates the formation of a cascade spatio-temporal response of the water system to anthropogenic and wartime impacts. Given that the city of Zaporizhzhia is subjected to more intense shelling, DVS-1 serves as the zone of primary formation of hydrochemical anomalies, whereas the water intake in the village of Bilenke is the site of their subsequent transformation and accumulation.

In the upper pool, a relatively stable oxygen and organic regime is generally observed: BOD_5 fluctuates within moderate values, and dissolved oxygen remains high. At the same time, COD shows a sharp increase in 2025 without a corresponding rise in BOD_5, which indicates the appearance of organic or technogenic compounds resistant to biochemical oxidation. In Bilenke, these processes manifest themselves differently: COD rises more gradually and persistently, without sharp peaks, which indicates not direct pulse impacts but the accumulation and transformation of pollutants carried by the current.

The most indicative difference is the dynamics of suspended solids. At monitoring point DVS-1, their increase is local and impulsive in nature, associated with direct physical disturbances of the hydrosystem, whereas in Bilenke, in 2025, a sharp and substantial increase in their concentration to more than 20 mg/dm^3 was recorded after a long period of stability. This indicates that material mobilized in the upper sections accumulates downstream, and that the additional involvement of bottom sediments in resuspension processes is also possible. At the same time, the absence of a sharp decrease in dissolved oxygen content in surface waters at both sites indicates the predominantly mineral or weakly biologically active nature of the suspended particles.

Biogenic elements show complex spatial differentiation. In the area of DVS-1, the content of ammonium and phosphate ions is characterized by sharp short-term peaks, which reflects pulsed inflows of pollution and disruption of the stability of biogeochemical processes.

In Bilenke, these same indicators display a smoother but more prolonged dynamics, which points to their gradual transport and secondary redistribution in the aquatic environment.

The nitrate content in both reaches changes relatively consistently; however, in the lower pool these fluctuations are less abrupt, which reflects the equalization of concentrations along the flow. Nitrite content remains low, but episodic peaks, more characteristic of DVS-1, indicate short-term disturbances of nitrification precisely in the zone exposed to more intense impacts.

Mineral components also show clear spatial differentiation. Sharp fluctuations of sulfates and chlorides are observed at DVS-1, especially in 2025, which reflects direct man-made influence and disturbance of the hydrochemical regime.

In Bilenke, these changes appear as a smoother but coordinated increase in both ions, which indicates their transport and accumulation in the lower part of the flow.

Summarizing, it is possible to note a fundamental difference between the two monitoring points (sections of the Dnipro River). At DVS-1, where the impact of military actions is more intense, hydrochemical indicators react quickly, sharply and impulsively, forming local anomalies.

In Bilenke, certain transformations do occur, yet persistent changes are present that reflect the processes of transport, mixing, and accumulation. Thus, the river system performs the function of

a natural integrator of impacts, where the upper pool is the zone of generation of hydrochemical disturbances and the lower pool is the zone of their accumulation and partial transformation. In the context of intensified shelling of Zaporizhzhia, this means that the upper section forms the primary ecological risks, while in the lower section they spread spatially and become fixed in the form of an altered hydrochemical background.

Conclusions. The analysis of hydrochemical indicators at the DVS-1 monitoring point for the period 2015-2026 indicates a generally relatively stable state of the water environment with periodic phases of destabilization, which are especially clearly manifested after 2024.

The organic load, reflected by BOD_5 and COD, has a moderate level in most of the period. At the same time, an atypical situation is recorded in 2025: the level of COD increases significantly (since July), while BOD_5 remains relatively stable. This is an anomaly that indicates an increase in the proportion of hard-to-oxidize organic or even inorganic reducing agents (for example, humic substances, man-made products), without a corresponding increase in biologically available organic substances.

The level of dissolved oxygen has seasonal dynamics: high values in the cold period and a decrease in the warm period. Its inverse relationship with BOD_5 and COD confirms the active use of oxygen in the processes of oxidation of organic matter. At the same time, the absence of a sharp drop in oxygen content even during periods of increased COD (especially in 2025) indicates sufficient aeration of water or the fact that a significant part of the substances that form COD is not involved in intensive biochemical oxidation.

The content of suspended solids remains stable for a long time (~5 mg/dm³), which is typical for conditions of a relatively stable hydrological regime. However, a sharp increase at the end of 2025 (up to 13 mg/dm³ and above) is an anomaly. Unlike previous years, when similar values did not exceed 6 mg/dm³ and increases were episodic in nature, this increase is long-lasting. It is probably related to local anthropogenic influence. It is important that this increase is accompanied by an increase in COD, which is consistent with the adsorption of organic substances on suspended particles. Therefore, suspended substances act as a carrier of organic load and additionally affect the oxygen regime, worsening the aeration conditions.

The dynamics of biogenic elements (ammonium and phosphate ions) reflects the variability of both internal processes and external inputs. Ammonium content is characterized by sharp but short-term peaks, which are a typical sign of the influx of fresh organic pollution or the activation of mineralization processes. The decline in ammonium after the peaks is usually associated with its oxidation to nitrites and nitrates. This is confirmed by the behavior of nitrates, which show a smoother but much broader amplitude of changes (up to 3-4 mg/dm³), with maxima in 2018-2020 and renewed growth in 2023-2024.

Nitrites, as an intermediate form, remain at a low level, but with episodic sharp spikes (especially at the beginning of the period, in 2021-2022 and 2024). Such peaks are an indicator of short-term nitrification disturbances or local oxygen deficiency in microzones. It is important that these spikes do not coincide with nitrate maxima, which indicates the rapid conversion of NO_2^- to NO_3^- and, in general, the effective flow of nitrification processes in the system.

The content of phosphate ions is unstable, especially after 2024, when their concentrations reach maximum values (0.6-0.75 mg/dm³). Unlike ammonium, their increases are of a longer duration and are often not synchronized with nitrogen forms. This indicates a different origin.

The mineral composition (sulfates and chlorides) generally reflects the background hydrogeochemical conditions, but also reacts to external influences. The content of sulfates has a larger amplitude of fluctuations and shows sharp peaks (2017 and especially 2025 — up to 90-95 mg/dm³), which can be associated with both natural processes (oxidation of sulfur-containing compounds) and technogenic influence. The content of chlorides remains stable for a long time, but from 2024 their concentration increases, and in 2025 sharp peaks are recorded (up to 60-70 mg/dm³). Synchronous growth of sulfates and chlorides in 2025 indicates a common source of income.

The impact of the war on the recorded dynamics of hydrochemical indicators at DVS-1 is indirect, but can be clearly traced through a set of anomalies that intensify after 2022 and especially in 2024-2025. It is important to understand that the war does not create «new» processes in the water environment, but sharply changes the intensity and balance of already existing ones - hydrological, biogeochemical, and anthropogenic.

Under conditions involving the use of Shahed-type strike drones and missiles, various substances may enter water bodies, simultaneously causing an increase in suspended solids and a rise in chemical oxygen demand (COD). The sources of such pollution include both explosion products and the components of the technical devices themselves, as well as materials from destroyed infrastructure.

First of all, a significant contribution is made by products of detonation of explosive substances containing organic compounds. During the explosion, partially oxidized organic

residues, nitro compounds and finely dispersed solid particles, in particular soot, are formed. These components increase COD as chemically oxidizable substances and at the same time form the fraction of suspended substances in water.

An important source is also fuel and lubricants - liquid hydrocarbon fuels, lubricating oils and hydraulic fluids, which can enter the water due to equipment damage. They are characterized by a high content of organic carbon, which leads to the growth of COD, and are also able to form emulsions or adsorb on solid particles, indirectly increasing the concentration of suspended substances.

A separate role is played by the debris of the hulls and structures of drones and missiles. Particles of metals, polymers, composites, rubber and insulating materials enter the water. In a finely dispersed state, they directly increase the content of suspended substances, and organic components of polymers with partial degradation can additionally affect the growth of COD.

Combustion products accompanying explosions and fires also have a significant impact. These include soot, polycyclic aromatic hydrocarbons and other partially oxidized organic compounds. They are simultaneously components of suspended substances and a source of increased COD.

In addition, construction materials that enter the water due to the destruction of structures make a significant contribution to pollution. These are cement dust, particles of concrete, bricks, silicates, as well as paints and coatings. Mineral components increase the content of suspended solids, while organic additives and coatings can increase COD.

In addition, heavy metals, electronic components, and electrolytes may appear in the water, which, although they do not always have a direct effect on COD, are capable of suppressing microbiological processes, changing the general nature of the transformation of pollutants.

The increase in ammonium-ion content in surface waters under wartime conditions may be associated with the thermal destruction of nitrogen-containing materials during explosions and fires, as well as with the decomposition of organic and technical substances containing nitrogen. Under normal conditions, ammonium in water undergoes nitrification with the formation of nitrites and nitrates, which is accompanied by oxygen consumption; however, under wartime conditions this process is often suppressed because of the toxic effect of impurities, high water turbidity, and disruption of the functioning of microbiocenoses. As a consequence, ammonium can accumulate in the aquatic environment without a significant effect on BOD_5 and without a noticeable decrease in dissolved oxygen.

Phosphate ions enter the water mainly as a result of the destruction of building materials, washing of dust from man-made surfaces, damage to infrastructure, as well as the release of compounds from soils and man-made deposits. The simultaneous increase of ammonium and phosphate ions at a stable level of dissolved oxygen and the absence of BOD_5 growth indicates the dominance of pulsed man-made input of substances and suppression of natural processes of nitrogen and phosphorus cycles. Under such conditions, the water system accumulates mineral forms of nitrogen and phosphorus without effective biological transformation, while changes in COD and suspended matter reflect the parallel arrival of organic and mechanical degradation products.

The increase in the content of sulfates can be associated with the oxidation of sulfur-containing compounds that are formed during fuel combustion and explosive processes. In particular, sulfur dioxide entering the atmosphere during combustion is oxidized to sulfuric acid in an aqueous environment and further transforms into the form of sulfate ions. An additional source is the destruction of building materials, in particular gypsum and cement components, which contain sulfate compounds. Industrial objects and dust aerosols of mineral origin can also contribute.

Chlorides can enter the water as a result of the burning of polymeric materials, especially those containing chlorine, such as polyvinyl chloride. During the thermal destruction of such materials, hydrogen chloride is formed, which transforms into chloride ions in an aqueous medium. In addition, the source of chlorides can be technical fluids, electrolytes, cooling mixtures and products of the destruction of engineering infrastructure. Chlorides are conservative ions, they do not decompose and are practically not removed from water by natural processes, therefore they tend to accumulate.

The overall dynamics of changes in hydrochemical indicators in the water of the Dnipro River (the village of Bilenke) in 2024-early 2026 indicate a relatively stable state of the oxygen and organic regimes against the background of more dynamic and, in places, anomalous changes in biogenic and mineral components.

Indicators of BOD_5 and dissolved oxygen show an inverse relationship typical for relatively clean or moderately polluted waters. During most of the period, BOD_5 is maintained at the level of 2.0-3.5 mg O_2/dm^3, while the concentration of dissolved oxygen remains high (8.5-10.5 mg O_2/dm^3). This indicates the balance of biochemical oxidation processes and sufficient water aeration. A slight decrease in oxygen in the first half of 2025 is accompanied by

a relative stabilization or even a decrease in BOD_5, which is atypical and may indicate not so much an increase in organic load, but the influence of the temperature factor (decrease in oxygen solubility in the warm period) or hydrobiological processes (increased respiration of hydrobionts). Further growth of BOD_5 in the second half of 2025 is logically consistent with an increase in the supply of organic matter (for example, during the summer-autumn development of phytoplankton or the washing of organic matter from the catchment).

At the same time, a sharp increase in the concentration of suspended solids in the fall of 2025 (over 20 mg/dm³) against the background of their long-term stability (4-5 mg/dm³) is abnormal. This phenomenon is probably of anthropogenic origin. It is important that this growth is not accompanied by a sharp increase in BOD_5 or a decrease in oxygen, which indicates the predominantly mineral nature of the suspended particles. At the same time, the increase in suspended solids could contribute to the adsorption of phosphates and temporary changes in their concentrations.

The content of ammonium ions increases in the spring (2024), which may be associated with flushing from the catchment and mineralization of organic matter, while the subsequent decrease is due to active nitrification. This is confirmed by the behavior of nitrates: their increase in spring and summer reflects intensive oxidation of ammonium. At the same time, the sharp increase in nitrates in the summer of 2025 after the spring minimum is an indicator of either increased inflow from the basin (agricultural runoff) or activation of nitrification processes under favorable temperature conditions.

Nitrites, as an unstable intermediate form, show episodic peaks, the most pronounced of which was recorded in August-September 2024. Such a surge is a classic sign of an imbalance between nitrification stages (oxidation of $NH_4^+ \rightarrow NO_2^- \rightarrow NO_3^-$) or local oxygen deficiency in microzones, even if the total content of dissolved oxygen remains high. This may be due to the arrival of fresh organic matter or local pollution.

Phosphate-ion content is the most variable indicator. Maxima, especially in September 2024 and in the summer-autumn period of 2025, indicate short-term inputs, most likely from wastewater and agricultural runoff. Importantly, these peaks are not always accompanied by a proportional increase in BOD_5, which may indicate rapid phosphate uptake by phytoplankton or their binding to suspended particles. The relationship between maxima of phosphate content and suspended solids at the end of 2025 may indicate intense resuspension processes in bottom sediments, where phosphorus accumulates in a bound form.

Mineral components (sulfates and chlorides) reflect both natural and anthropogenic factors. The sulfate content has peaks (up to more than 80 mg/dm³ in 2025), which may be related to industrial discharges or oxidation of sulfur-containing compounds. The content of chlorides does not have sharp maxima, but its increase in 2025 (up to 60-65 mg/dm³) indicates an increase in anthropogenic influence (domestic sewage, man-made load). Concordant chloride and nitrate maxima in 2025 may indicate a common source.

For the water intake in the village of Bilenke, the influence of wartime factors likewise manifests itself not as a simultaneous deterioration of all indicators, but as a disruption of the stability of the hydrochemical regime, the appearance of sharp impulse changes, and atypical combinations of indicators, especially in 2024-2025.

First of all, this is visible against the background of a generally stable oxygen and organic regime. BOD_5 throughout the period remains within moderate values, and dissolved oxygen is high. This means that there was no mass influx of easily oxidizable organic matter (for example, large volumes of domestic sewage). At the same time, such «normality» is somewhat misleading, since other indicators show significant disturbances. That is, the war is manifested here not because of classic organic pollution, but because of another type of influence - hydrological and man-made.

The most telling is the sharp increase in suspended solids in the fall of 2025 (more than 20 mg/dm³ after a long-term level of 4-5 mg/dm³). Such a change has the characteristics of a military or related influence. It is important that this increase is not accompanied by a proportional increase in BOD_5 and a drop in oxygen, that is, suspended substances are mainly of mineral or weakly bioavailable origin. This is a typical indicator of mechanical (rather than organic) disruption of the system, which corresponds well with the consequences of military actions.

Thus, in the area of the drinking water intake in the village of Bilenke, the influence of the war manifests itself as a sharp increase in suspended solids without deterioration of the oxygen regime; pulse-like inputs of pollutants, including peaks in phosphate and nitrite content; changes in water mineralization, including the synchronous increase in sulfate and chloride content; and so forth.

Importantly, unlike DVS-1, where the technogenic component is more clearly manifested through COD, in Bilenke the hydrological-geochemical effect predominates - that is, the impact exerted through changes in the physical state of the system (channel, bottom sediments, runoff), and not solely through direct chemical pollution.

Thus, comparing the hydrochemical data with periods of intensified shelling of the city of

Zaporizhzhia makes it possible to interpret the recorded changes as a consequence of short-term but intense inputs of destruction and combustion products into the river system. This is manifested in the form of increasing COD and suspended solids under a relatively stable oxygen regime, which is characteristic of an impact type of pollution rather than of a prolonged organic load. In addition, in our opinion, one may also speak of a cumulative effect of previous impacts which, under conditions of intensified shelling of the city, manifested themselves in the form of the anomalies under study.

In sum, it is more appropriate to speak not of a catastrophic deterioration in water quality, but of the system's transition to an unstable state, in which, even under normal average values, the frequency and amplitude of anomalies increase sharply, which is a characteristic sign of the influence of wartime factors on aquatic ecosystems.

Конфлікт інтересів: автори повідомляють про відсутність конфлікту інтересів

Внесок авторів: Лідія Горошкова – концептуалізація, розробка ідей, аналіз та інтерпретація даних, написання статті; Олександр Меньшов – розробка ідей, аналіз та інтерпретація даних, моделювання, написання статті; Денис Маслов – аналіз та інтерпретація даних, написання статті; Юлія Корнійчук та Станіслав Горошков – збір первинних даних, їх систематизація та обробка

Декларація про використання генеративного штучного інтелекту: Автори використовували інструменти генеративного штучного інтелекту (GenAI) для допоміжної роботи: мовне редагування та коректура рукопису були виконані з використанням моделі ШІ ChatGPT (OpenAI). Усі результати роботи з цими інструментами були ретельно контрольовані, перевірені та, за необхідності, відредаговані авторами. Автори несуть повну відповідальність за зміст та цілісність публікації.

Подяка: Дослідження виконано в межах проєкту 0124U004208 «Еколого-економічна оптимізація логістичної інфраструктури в умовах війни та повоєнної відбудови України», що реалізується в рамках програми наукової роботи, науково-технічних та інфраструктурних проєктів, які фінансуються за рахунок коштів спеціального фонду, отриманих від інструменту зовнішньої допомоги Європейського Союзу для виконання зобов'язань України в Рамковій програмі ЄС з досліджень та інновацій «Горизонт 2020».

Conflict of Interest: The authors declare no conflict of interest

Authors Contribution: Lidiia Horoshkova – conceptualization, idea development, data analysis and interpretation, article writing; Oleksandr Menshov – idea development, data analysis and interpretation, modeling, article writing; Denys Maslov – data analysis and interpretation, article writing; Yuliia Korniichuk and Stanislav Horoshkov – collection of primary data, its systematization and processing

Declaration of use of generative artificial intelligence: The authors utilized generative artificial intelligence (GenAI) tools in a supportive capacity: language editing and proofreading of the manuscript were performed using the ChatGPT AI model (OpenAI). All outputs from these tools were carefully supervised, reviewed, and, where necessary, edited by the authors. The authors retain full responsibility for the content and integrity of the publication.

Acknowledgments. The research was carried out under project 0124U004208 «Ecological and economic optimization of logistics infrastructure during war and post-war reconstruction of Ukraine», implemented as part of the scientific work program, scientific-technical and infrastructure projects funded from special fund resources obtained from the European Union's external assistance instrument for fulfilling Ukraine's obligations in the European Union Framework Programme for Research and Innovation «Horizon 2020».

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Дослідження впливу війни на гідрохімічні показники поверхневих вод річки Дніпро в межах міста Запоріжжя і Запорізького району

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АНОТАЦІЯ

Річка Дніпро є однією з найбільших річкових систем Європи та ключовим джерелом поверхневих вод України, що забезпечує функціонування промислових, комунальних і аграрних водогосподарських комплексів. У межах Запоріжжя та Запорізького району річкова система зазнає кумулятивного впливу багаторічного антропогенного навантаження, зумовленого високою концентрацією металургійної, енергетичної та хімічної промисловості, а також значною зарегульованістю стоку внаслідок функціонування каскаду дніпровських водосховищ. Це формує складний багатокомпонентний гідрохімічний режим із вираженою просторово-часовою неоднорідністю показників якості води. Водночас із 2022 року функціонування басейну Дніпра зазнало впливу додаткового екстремального чинника - воєнних дій, які істотно змінили структуру та інтенсивність антропогенних впливів на водні екосистеми. У роботі представлено результати комплексної екологічної оцінки якості поверхневих вод річки Дніпро в межах м.Запоріжжя та Запорізького району (с. Біленьке). Аналіз гідрохімічних показників у пунктах моніторингу ДВС-1 і с. Біленьке за 2015–2026 рр. свідчить про загалом відносно стабільний стан водного середовища з переходом до нестійкого режиму після 2022 року та особливо у 2024–2025 рр. Показано, що для ДВС-1 характерне підвищення ХСК без відповідного зростання $БСК_5$, збільшення вмісту завислих речовин і мінеральних компонентів (сульфатів і хлоридів), що вказує на надходження важкоокиснюваних і техногенних домішок внаслідок обстрілів міста. У с. Біленьке за збереження стабільного кисневого режиму фіксується різке зростання завислих речовин переважно мінерального походження, а також імпульсні зміни біогенних елементів внаслідок інтенсивного забруднення поверхневих вод вище за течією (ДВС-1). Виявлені особливості інтерпретуються як наслідок воєнного впливу, який проявляється через короткочасні інтенсивні надходження продуктів руйнування і горіння внаслідок підвищення інтенсивності обстрілів м. Запоріжжя у 2025 – 2026 рр., зміну гідрологічного режиму та пригнічення природних біогеохімічних процесів.

ІНФОРМАЦІЯ ПРО СТАТТЮ :

Рукопис надійшов
20 березня 2026

Отримано після рецензування
3 травня 2026

Затверджено до друку
25 травня 2026

Опубліковано онлайн
30 травня 2026

Ключові слова:

поверхневі води, екологічна оцінка, антропогенне навантаження, забруднення вод, вплив війни, гідрохімічні показники, антропогенний вплив, військовий вплив, річка Дніпро, якість поверхневих вод.

https://doi.org/10.26565/2410-7360-2026-64-28

УДК 911.9:504.5

Польові дослідження мілітарних забруднень ґрунтів агроландшафтів важкими металами

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АНОТАЦІЯ

Розглядається науково-прикладний потенціал методики ландшафтно-екологічного аналізу для обґрунтування стратегії польових досліджень мілітарних забруднень ґрунтів агроландшафтів важкими металами. Позиційно-динамічна ландшафтна територіальна структура, що змодельована із застосуванням інструментарію геопросторового аналізу відкритих даних, визначається як базова для синтезу інформації про агроландшафтне різноманіття територій. Агроландшафт править за об'єкт польових досліджень мілітарних забруднень ґрунтів. Зазначено, що ґрунти є визначальним складником агроландшафту, однак сценарії поведінки забрудників в довкіллі, а саме первинний та вторинний їхній розподіл, зумовлено властивостями цілісних, відособлених та відносно однорідних природно-виробничих систем. А отже риси формування і розвитку агроландшафтів з однаковою агровиробничою групою ґрунтів, розміщених в різних позиційно-динамічних і геоморфологічних умовах, суттєво різняться за складом, напрямком та інтенсивністю всіх фізико-хімічних процесів. Подано результати апробації розробленої стратегії польових досліджень ґрунтів агроландшафтів, отримані під час польових досліджень Шевченківської об'єднаної територіальної громади. Стратегія відбирання проб ґрунтів на обраних дослідних ділянках агроландшафту визначалась результатами аналізу досвіду подібного пробовідбору ґрунтів, які зазнали бомбтурбацій, камеральними передпольовими узагальненнями всіх передумов робіт in situ та експертно-аналітичними рішеннями в процесі польових досліджень. Окреслено потенціал екстраполяції отриманих результатів. Новизна проведених розвідок

ІНФОРМАЦІЯ ПРО СТАТТЮ :

Рукопис надійшов
2 січня 2026

Отримано після рецензування
7 лютого 2026

Затверджено до друку
25 травня 2026

Опубліковано онлайн
30 травня 2026

Ключові слова:

мілітарні забруднення, важкі метали, ландшафтно-екологічний аналіз, геопросторовий аналіз, позиційно-динамічні умови, стратегія польових досліджень ґрунтів, агроландшафт, екстраполяція результатів, відновлення ґрунтів

Як цитувати : Денисик Григорій, Запотоцький Сергій, Самойленко Віктор, Білоус Людмила, Циганок Євген, Гура Костянтин, Галаган Олександр, Кандій Марія, Нагорна Наталя (2026). Польові дослідження мілітарних забруднень ґрунтів агроландшафтів важкими металами. *Вісник Харківського національного університету імені В.Н. Каразіна Серія «Геологія. Географія. Екологія»*, (64), 369–382. https://doi.org/10.26565/2410-7360-2026-64-28

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визначається обґрунтованою та апробованою методикою, об'єктом і стратегією відбирання проб при польовому дослідженні мілітарного забруднення ґрунтів агроландшафтів. Результати дослідження є релевантними для запровадження ефективних програм дослідження й аналізу стану ґрунтів і використання цих результатів при розробці уніфікованої на рівні держави процедури вивчення і оцінки стану забруднених війною ґрунтів для їхнього відновлення.

Вступ

Згідно зі щорічним звітом «Російсько-українська війна: вплив на довкілля», станом на 13.09.2024 площа ґрунтів, які постраждали від воєнних дій, становить 20,8 млн м^2 [1]. 18% виробників рослинної продукції по країні та 38% у прифронтових регіонах (Херсонська область – 94%) повідомляють про забруднення полів мінами і нездетонованими боєприпасами [2].

«Стратегія розвитку сільського господарства та сільських територій в Україні на період до 2030 року» [3] визначає забезпечення стійкості як стратегічну ціль, співзвучну з такими цілями сталого розвитку ООН, як подолання бідності та голоду в умовах миру та справедливості [4]. Для реалізації стратегії виокремлено, зокрема, завдання проведення оцінки забруднення ґрунтів, організації систем їхнього моніторингу та надання рекомендацій щодо оптимальних шляхів відновлення [3].

Виконання зазначеного завдання має відбуватись у поєднанні з ландшафтно-екологічними дослідженнями агроландшафтного різноманіття територій та вивченням стану агроландшафтів. Важливим складником досліджень мілітарних забруднень ґрунтів агроландшафтів, серед них важкими металами, є польовий етап з відбиранням проб ґрунтів для лабораторних вимірювань. Обґрунтування стратегій польових досліджень мілітарно змінених ґрунтів агроландшафтів є нагальними та актуальним для наукових розвідок і вишукувань.

Аналіз попередніх досліджень і публікацій. Науковий доробок ландшафтно-екологічного аналізу (далі, скорочено, ЛЕА) та агроландшафтних досліджень сформовано згідно з теоретико-методичними засадами: регіональних природознавчих досліджень території України [5]; ландшафтної екології [6]; ландшафтно-екологічного аналізу природокористування та ландшафтного планування і проєктування [7-11]; антропізації ландшафтів [12]; агроекології [13]; геохімії ландшафтів [14]; еколого-геохімічних досліджень міграції важких металів в агроландшафтах [15]; ландшафтно-екологічного геопросторового аналізу та моделювання [16, 17].

Зараз в Україні активно досліджується мілітарне забруднення ґрунтів. Зокрема, отримано досвід комплексних досліджень воєнного впливу на ґрунти, зважаючи на морфологічні та морфометричні параметри рельєфу і сучасні геоморфологічні процеси та системи землекористування [18]. У 2023 р. видано «Методичні рекомендації з відбору проб ґрунту в зонах бойових дій» [19]. Державною установою «Інститут охорони ґрунтів України» у 2023 р. було проведено обстеження ґрунтового покриву ділянок, які зазнали впливу бойових дій [20]. Важливим є досвід досліджень мілітарного впливу снарядів різного типу на ґрунти [18, 21]. Результати аналізу наукового доробку досліджень мілітарного впливу на ґрунти дозволяють констатувати відсутність ґрунтовних праць з результатами вивчення агроландшафтів та змінених в їхньому складі грунтів.

Дослідження мілітарних забруднень ґрунтів виконуються у складі міжнародних проєктів. КНУ імені Тараса Шевченка у співпраці з Технологічним університетом Чалмерса (Швеція) та WWF-Україна за фінансової підтримки Шведського інституту виконує наукові дослідження за проєктом «RECOVER: Кліматично розумне відновлення сільського господарства на розмінованих територіях України» (далі, скорочено, проєкт RECOVER). Кінцевим завданням проєкту RECOVER є модельне оцінювання ймовірності мілітарного забруднення продукції агроландшафтів важкими металами за результатами та даними лабораторно-польових вимірювань відібраних проб ґрунту [22].

Результати моделюванням переходу забруднювальних речовин з ґрунту до агропродукції, зокрема пшениці, розглянуто в низці праць [23-25]. Зокрема, вивчався перехід свинцю у пшеницю [23], вплив вмісту важких металів у ґрунті на перенесення кадмію з нього у пшеницю [24] та поглинання важких металів озимою пшеницею та фуражною кукурудзою [25].

Виділення невирішених раніше частин загальної проблеми. Кабінет Міністрів України 14.07.2025 прийняв постанову № 844 «Про затвердження Порядку відбору проб ґрунтів на землях сільськогосподарського призначення, очищених від вибухонебезпечних предметів» [26]. Пунктом 3 цієї постанови передбачено затвердити відповідні методичні рекомендації. Наразі даний документ не розроблено.

Досвід та методи польових досліджень грунтів в Україні регламентуються міжнародними та державними стандартами [27-33]. Зміст програми польових досліджень грунтів (далі, скорочено, Програма) регламентується стандартом ДСТУ ISO 10381-1:2004 [28], де і ви-

значаються її відповідні етапи, а саме: 1) визначення завдання всього дослідження, складання списку параметрів ґрунту, які заплановано дослідити; 2) збір та аналіз попередньої інформації про об'єкт польових досліджень; 3) обґрунтування стратегії відбирання проб (далі, скорочено, Стратегії); 4) відбирання проб; 5) підготовка звіту про відбирання проб. Визначена цим стандартом етапність є актуальною для досліджень мілітарних забруднень ґрунтів агроландшафтів. Однак етап Стратегії потребує науково-дослідної уваги до експериментально-експертних рішень в умовах мілітарних змін довкілля, зокрема й агроландшафтів.

Метою дослідження є розгляд питань пізнання агроландшафтного різноманіття території в результаті ЛЕА та обґрунтування, розробка і пілотна апробація Стратегії відбирання проб ґрунтів агроландшафтів, мілітарно змінених масованими бомбтурбаціями невкеровними авіаційними ракетами (далі – НАР) С-8, для лабораторних досліджень міри їхнього забруднення важкими металами.

Методи дослідження. Розробка Стратегії, як визначального етапу Програми, базувалась на результатах аналізу чинних національних і міжнародних стандартів відбору проб ґрунтів, галузевих інструкцій, спеціалізованих методичних рекомендацій для територій, зазнавших мілітарного впливу, та власних експертно-аналітичних досліджень, зокрема за проєктом RECOVER.

За першим етапом Програми було визначено завдання всього дослідження, а саме вимірювання параметрів мілітарно змінених ґрунтів агроландшафту, необхідних для моделювання ймовірності забруднення посівів пшениці в разі її культивації в агроландшафті. Камеральний передпольовий етап дослідження потребував насамперед застосування системи аналітично-експертного прийняття рішень за результатами вивчення низки праць (див. аналіз попередніх публікацій) для вибору переліку параметрів ґрунтів агроландшафтів, важливих для визначення. Обраний таким чином перелік містить: вміст важких металів, а саме загальний вміст свинцю (Pb) і вміст свинцю екстрагованого EDTA (етилендіамінтетраоцтовою кислотою), загальний вміст міді (Cu) і цинку (Zn), загальний вміст та вміст обмінної форми кадмію (Cd); супутні для модельного оцінювання ймовірності мілітарного забруднення сільськогосподарської продукції параметри ґрунту, серед них pH, вміст ґрунтового кальцію (Ca) і органічної речовини та електропровідність.

Для обґрунтування і розробки стратегії дослідження ґрунтів агроландшафту за базову правила методика ЛЕА територій, а також підходи до геоінформаційного забезпечення територіальних громад, викладені у [34].

Система методів збору та аналізу попередньої інформації про об'єкт польових досліджень, на базі якого планувались обґрунтування та розробка Стратегії дослідження, була не детермінованою з об'єктивних безпекових причин. Дослідна ділянка обиралась ситуативно. Певна визначеність існувала стосовно об'єднано-територіальної громади (далі, скорочено, ОТГ), в межах якої було заплановано проведення польових досліджень. Відповідно, було зібрано та проаналізовано попередню інформацію та відкриті геопросторові дані про об'єкт польового дослідження, а саме Шевченківську ОТГ у Миколаївській області.

Камеральний передпольовий етап дослідження передбачав роботу на трьох масштабних територіальних рівнях: 1:100 000, 1:50 000 та 1:25 000. Було використано джерельну базу відкритих геопросторових даних, зокрема дані Публічної кадастрової карти України [35] для ідентифікації агровиробничих груп ґрунтів і дані радарного знімання SRTM [36] для аналізу цифрової моделі рельєфу (далі, скорочено, ЦМР) та моделювання елементів позиційно-динамічної ландшафтно-територіальної структури (далі, скорочено, ПД ЛТС).

За допомогою геоінформаційних технологій із застосуванням ГІС-інструментарію ArcGIS та QGIS було проведено геопросторовий аналіз ЦМР для синтезу позиційно-динамічних характеристик території дослідження та виділення парадинамічного району (далі, скорочено, ПДР), ландшафтних ярусів та ландшафтних смуг як складників ПД ЛТС. Останні виокремлюються за напрямом та інтенсивністю сучасних фізико-географічних процесів та є територіальним базисом виділення агроландшафтів.

Результати камерального передпольового етапу використовувалися для обґрунтування та розробки Стратегії відбирання проб ґрунтів агроландшафтів. При цьому було використано консультативні поради фахівців кафедри географії природничо-географічного факультету Вінницького державного педагогічного університету імені Михайла Коцюбинського та фахівців Харківського національного університету імені В.Н. Каразіна [37]. Польовий етап дослідження містив насамперед рекогносцирувальне обстеження території досліджень з метою візуальної ідентифікації агроландшафту і локацій мілітарного впливу на нього (вирви вибухів, сліди пересування військової техніки, траншеї, насипи), оцінки ступеня механічного порушення ґрунтового покриву, попереднього візуально-аналітичного зонування агроландшафту за рівнем потенційного забруднення. Ідентифікація мілітарно трансформованих ділянок в межах конкретного агроландшафту відбувалася з використанням експертно-ана-

літичного методу, що базується на аналізі морфології форм вирв, характеру механічних порушень ґрунтового покриву та геопросторової конфігурації зон ураження. У польових умовах відбиралися гніздові (композитні) проби шляхом змішування точкових проб (по 21 пробі). Розмір дослідної ділянки, схеми відбору проб на ділянці, маршрутний хід польового дослідження були обумовлені експертно визначеною методикою відбору проб ґрунту.

Відбирання проб ґрунтів агроландшафтів, яке є четвертим етапом Програми та підтримує дослідницьке завдання з апробації Стратегії, було заплановано реалізовувати за принципами достовірності та відтворюваності результатів: орієнтування точок пробовідбору за сторонами світу та фіксація координат кожної точки відбору проб за допомогою GPS-приймача. Важливою вбачалась і діяльність з фотозйомки точок відбору проб і характерних форм мілітарного впливу, фіксації розмірів та глибини воронок, документування стану ґрунтового покриву як індикатора ґрунтових змін. У процесі відбирання проб ґрунту за обов'язковий етап править їхнє маркування та пакування для транспортування, в цьому випадку до навчально-наукової лабораторії екології ландшафту кафедри фізичної географії та геоекології LandscapeLabKNU географічного факультету КНУ імені Тараса Шевченка.

За п'ятим етапом Програми було передбачено підготовку звіту про відбирання проб ґрунтів агроландшафтів і презентації висновків про перспективи екстраполювання результатів польових і лабораторних досліджень агроландшафту.

Наукова доцільність та потенціал ефективності і результативності польових і лабораторних досліджень мілітарного забруднення ґрунтів агроландшафтів зумовлює необхідність моделювання агроландшафтів та їхньої інформаційної інвентаризації як об'єкта дослідницьких ітерацій. Ландшафтно-екологічний аналіз здатен забезпечити можливість змоделювати агроландшафти як певні природно-виробничі генетико-морфологічні та процесно-функціональні цілісності, які характеризуються особливими та відносно однорідними ландшафтно-геохімічними та ландшафтно-геофізичними проявами. Такий аналіз забезпечує можливість репрезентативного відбирання проб ґрунтів агроландшафтів та синтезу інформації для екстраполювання результатів польових та лабораторних досліджень на подібні агроландшафти з таким самим мілітарним впливом. Більше того, ЛЕА продукує знання з географії та різноманіття агроландшафтів, що є основою розробки систем моніторингу та відновлення агровиробничих земель.

Результати дослідження. Ландшафтно-екологічний аналіз для моделювання агроландшафтів, як об'єктів польових досліджень мілітарного забруднення грунтів важкими металами, було проведено для Шевченківської ОТГ Миколаївського району Миколаївської області (рис. 1). Дослідження здійснювались, зокрема, в межах виконання завдань проєкту RECOVER.

У Шевченківській ОТГ налічується 14 сіл та 7 селищ. Громада межує з Херсонською областю, розташована в середньостеповій та південностеповій підзонах степової зони та має

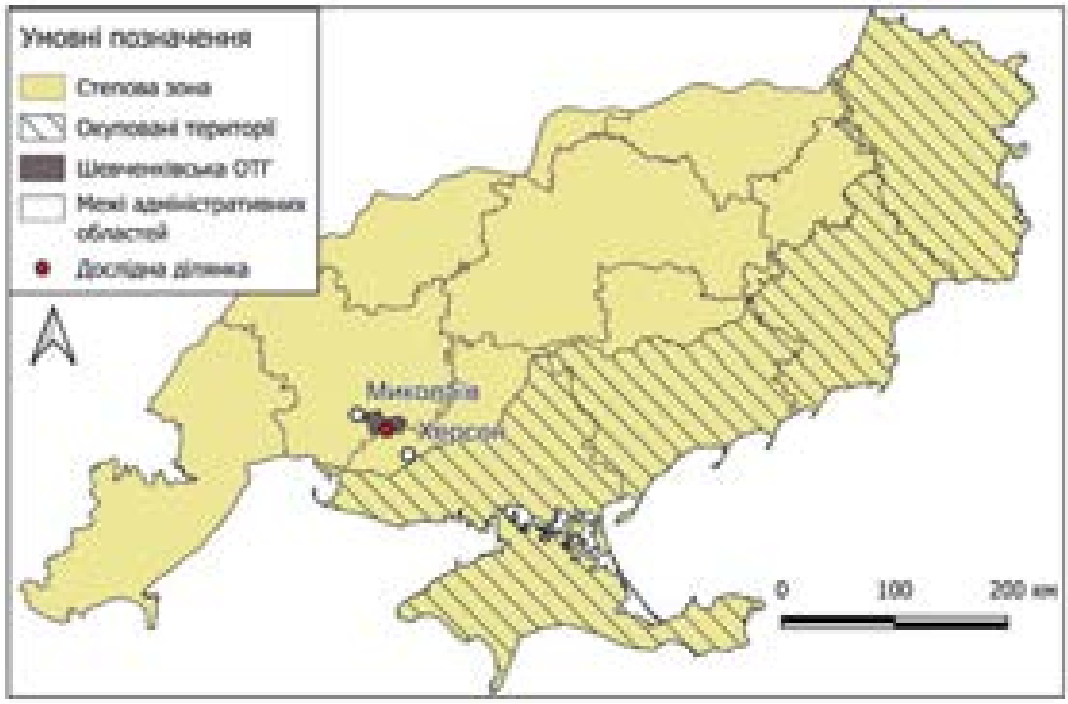


Рис. 1. Дослідні ділянки в межах степової зони та по відношенню до окупованої території України станом на 16.11.2025 за [38-40] / **Fig. 1.** Research areas within the steppe zone and in relation to the occupied territory of Ukraine as of 16.11.2025 according to [38-40]

агровиробничу спеціалізацію. Система сталого управління землекористуванням в ОТГ визначається територіальною структурою та різноманіттям агроландшафтів.

У ході ЛЕА, із застосуванням інструментарію ArcGIS та QGIS для геопросторового аналізу ЦМР, було отримано елементи ПД ЛТС, які визначають морфологію агроландшафтів та інтенсивність і напрямок їхніх позиційно-динамічних взаємодій.

Позиційно-динамічні риси територіальної організації агроландшафтів Шевченківської ОТГ сформовано речовинно-енергетичними потоками в басейнах р. Інгул та р. Веревчина (рис. 2). За результатами геопросторового аналізу ЦМР зазначених басейнів було виділено Інгуло-Веревчинський ПДР. Класифікація його ЦМР за методом середньоквадратичного відхилення дозволила виокремити в межах цього району ландшафтні яруси: I-й – пластово-денудаційних низовин (80-50 м), ускладнених суфозійно-просадковими процесами, раніше під типчаково-ковиловою та лучною рослинністю; II–й – пластово-акумулятивних низовин (50-30 м), ускладнених суфозійно-просадковими процесами, раніше під типчаково-ковилово-полиновою та лучною рослинністю; III-й – транселювіальний схиловий з ерозійними проявами, ускладнений ярами та балками під типчаково-ковиловою рослинністю; IV-й – трансакумулятивний терасово-заплавний під лучною рослинністю (рис. 2).

Результативність оверлейного моделювання агроландшафтів I-го та II-го ландшафтних ярусів в межах Шевченківської ОТГ визначалась детальністю та достовірністю вихідних для моделювання моделей геотопів ландшафтних смуг, виділених за ухилами і висотами, та агровиробничих груп ґрунтів (рис. 2). I-й та II-й ландшафтні яруси континуально перетворені агровиробничою діяльністю і, відповідно, можуть бути визначені як агроландшафтні яруси ПДР з певним складом ландшафтних смуг (агроландшафтів). I-й агроландшафтний ярус ПДР розташовано в середньостеповій підзоні Причорноморському середньостеповому

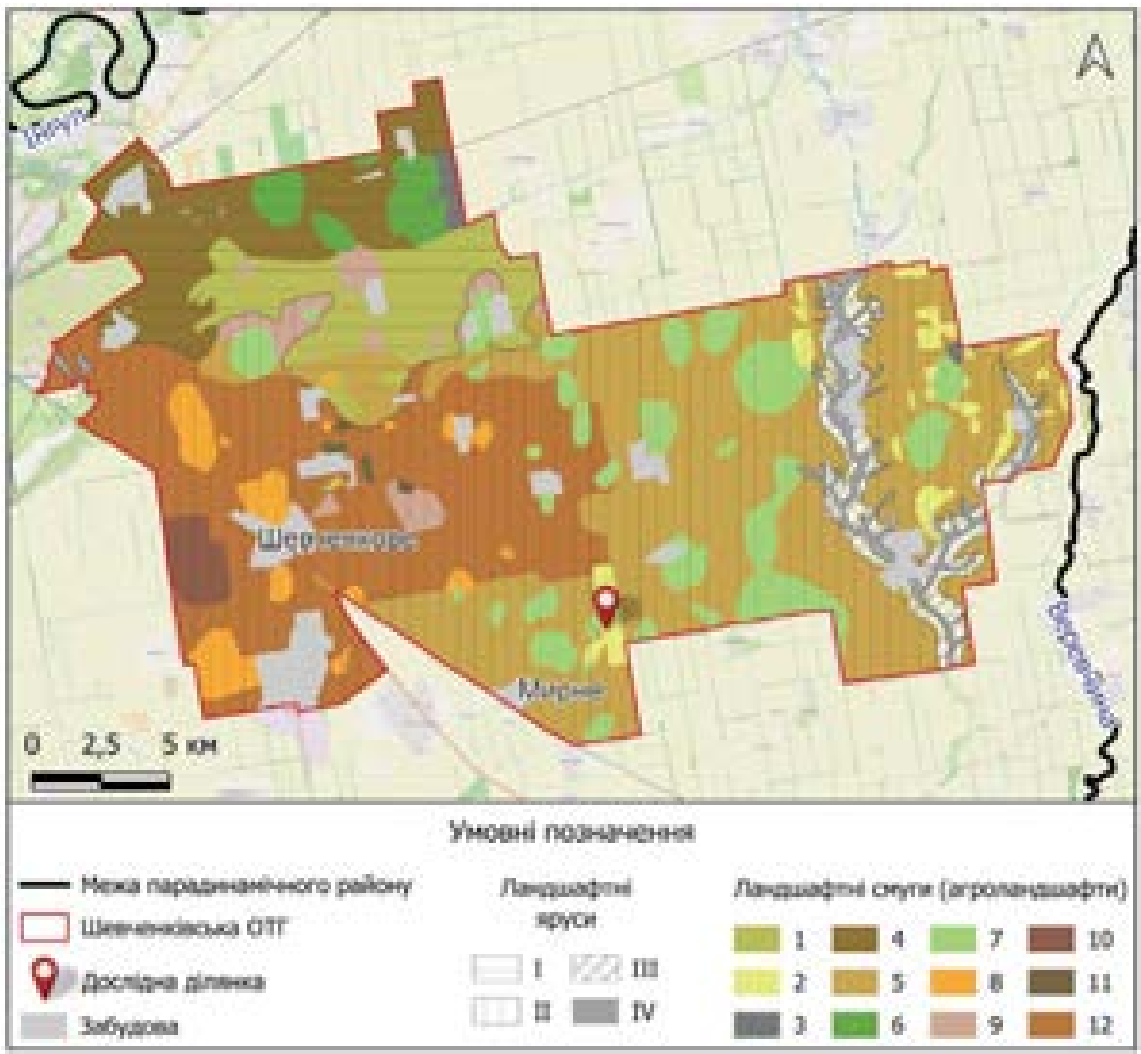


Рис 2. Агроландшафти Шевченківської ОТГ в межах позиційно-динамічної ландшафтно-територіальної структури /
Fig. 2. Agrolandscapes of Shevchenkivska UTC within the positional-dynamic landscape-territorial structure

краї. У Шевченківській ОТГ цей ярус представлено Лівобережно-Інгульським районом Бузько-Дніпровської низовинної області [40]. Його зональними агроландшафтами є елювіальні плато пластово-денудаційних низовин з чорноземами південними малогумусними легкосуглинковими, місцями важкосуглинковими в комплексі із засоленими їхніми відмінами на лесах (1, 3, 4 на рис. 2). ІІ-й агроландшафтний ярус ПДР розташовано в південностеповій підзоні Причорноморсько-Приазовському краю. У Шевченківській ОТГ цей ярус представлено Посад-Покровсько-Білозерським районом Нижньобузько-Дніпровської низовинної області [40]. Його зональними агроландшафтами є елювіальні плато пластово-акумулятивних низовин з каштановими, темно-каштановими малогумусними важкосуглинковими, місцями легкосуглинковими ґрунтами в комплексі із засоленими їхніми відмінами на лесах (10, 11, 12 на рис. 2) та чорноземними південними малогумусними важкосуглинковими, місцями легкосуглинковими ґрунтами в комплексі із засоленими їхніми відмінами на лесах (2, 5 на рис. 2).

Агроландшафтне різноманіття І-го ярусу ПДР в межах Шевченківської ОТГ формують ландшафтні смуги: елювіально-гідроморфні подових суфозійно-просадкових увігнутих пластово-денудаційних лесових низовин з лучно-чорноземними глеюватими і глейовими легкосуглинковими та важкосуглинковими ґрунтами в комплексі з лучними глейовими та солодами на лесах (6 на рис. 2) та, екотонно зумовлені, з лучно-каштановими глеюватими і глейовими важкосуглинковими та легкосуглинковими ґрунтами в комплексі з солончаковими їхніми відмінами (9 на рис. 2). Агроландшафтне різноманіття ІІ-го ярусу ПДР формують елювіально-гідроморфні смуги подових суфозійно-просадкових увігнутих пластово-акумулятивних лесових низовин з лучно-каштановими глеюватими і глейовими важкосуглинковими та легкосуглинковими ґрунтами в комплексі з солончаковими їхніми відмінами (8, 9 на рис. 2) та з лучно-чорноземними глеюватими і глейовими важкосуглинковими та легкосуглинковими ґрунтами в комплексі з лучними глейовими та солодами (7 на рис. 2).

Польові дослідження ґрунтів було проведено на території агроландшафту елювіальних пластово-акумулятивних лесових низовин з чорноземами південними вторинно підтопленими малогумусними важкосуглинковими на лесах в локації біля с. Мирне (2 на рис. 2).

Результати дослідження може бути екстрапольовано на такі ж самі агроландшафти ІІ-го ярусу ПДР з аналогічним мілітарним впливом. На території Шевченківської ОТГ їхня площа становить 11,52 км².

Стратегія відбирання проб ґрунту агроландшафту, що зазнав мілітарного впливу НАР С-8, визначається: глибиною відбирання гніздових проб, схемами та способом відбирання таких проб, а також стандартизовано визначеними інструментарієм, способами маркування, пакування і транспортування зазначених проб.

Оптимальною для відбирання проб ґрунту було визначено глибину 1-5 см як найбільш імовірне депо досліджуваних мілітарних за-

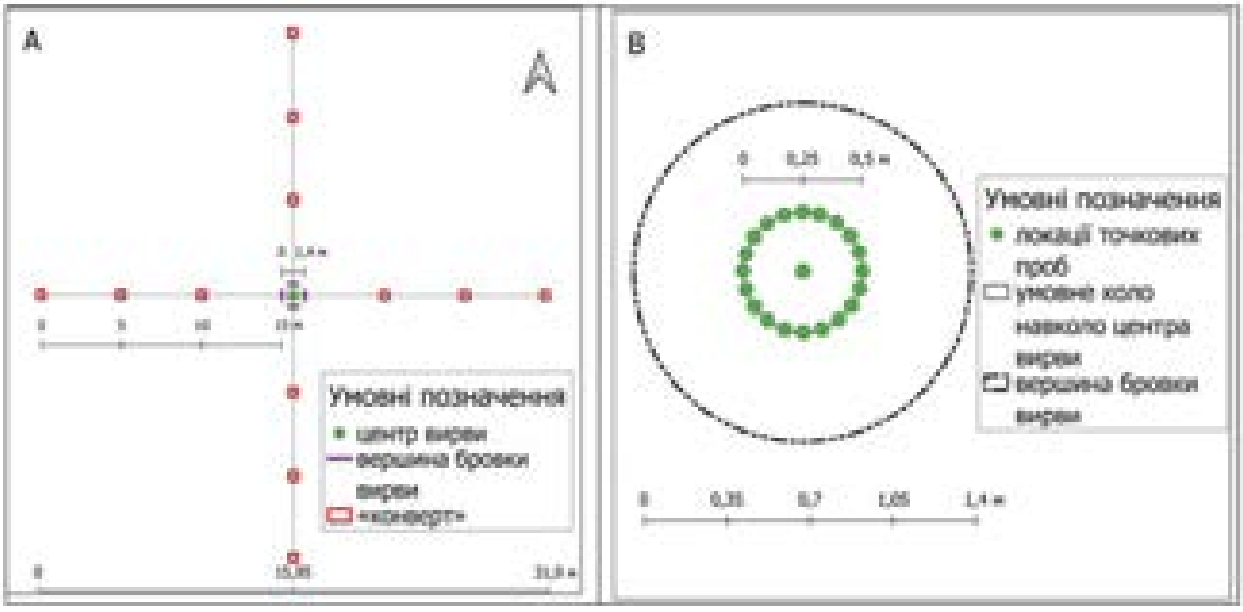


Рис. 3. Схема маршрутного ходу польового відбору проб ґрунту на дослідній ділянці довкола вирви (А) та схема відбору гніздової проби по колу в центрі вирви (В) /
Fig. 3. Scheme of the field research route run in the research plot around the crater (A) and scheme of circular cluster sampling in the center of the crater (B)

брудників ґрунту. Це зумовлено природними чинниками структурно-функціональної організації агроландшафтів, станом ділянки і засвідчено досвідом колег [18, 19]. Додатково брались до уваги і результати праці [21], де було детально проаналізовано особливості міграції забруднювальних речовин воєнного походження у ґрунтах. Автори цієї праці дійшли висновку, що органічна речовина та глиниста фракція ґрунту, що і притаманно дослідним ділянкам агроландшафту, істотно уповільнюють вертикальну міграцію важких металів за ґрунтовим профілем.

Для репрезентативності результатів дослідження та згідно з Інструкцією [41] було прийнято рішення про здійснення гніздового відбору проб ґрунту на дослідних ділянках. Гніздова проба визначається Державним стандартом [29] як «об'єднана проба, яку отримують шляхом змішування кількох точкових проб (або «гнізд»), відібраних в попередньо визначеній точці та навколо неї».

Прийняття рішення щодо кількісного складу точкових проб в гніздовій пробі також має регламентуватися результатами експертного аналізу дослідних ділянок. Було визнано за доцільне відбирати по 21 точковій пробі ґрунту для кожної гніздової проби на відповідних локаціях дослідних ділянок.

Попередній огляд та аналіз імовірних дослідних ділянок став ключовою передумовою обґрунтування схеми маршрутного ходу польового дослідження на кожній ділянці. Проведений аналіз досвіду пробовідбору ґрунтів, які зазнали бомбтурбацій [18, 19, 21], і камеральні передпольові узагальнення всіх передумов роботи *in situ* і дозволили розробити відповідну схему маршрутного ходу на дослідній ділянці (рис. 3, А). Вибір наведеної далі схеми маршрутного ходу польового відбору проб ґрунту пояснюється головним чином необхідністю обстеження невеликих за розмірами потенційних дослідних ділянок і відносно невеликою відстанню між мілітарними вирвами в агроландшафті.

Початковою точкою маршрутного ходу пробовідбору ґрунту на кожній дослідній ділянці було визначено днище вирви. Воно характеризує зону максимального осідання та потенційного накопичення дрібнодисперсного матеріалу після вибуху. До такого днища вирви має бути приурочено відбір першої гніздової проби. Далі маршрут має продовжуватися у чотирьох напрямках, орієнтованих за сторонами світу, через вершину бровки вирви. Така вершина як квазілінійний замкнутий об'єкт облямовує зазначену бровку, яка виглядає як «міні-пагорб», що утворюється навколо вирви внаслідок викиду та перерозподілу ґрунтової маси під час вибуху. Для кожного з напрямів від вершини бровки проби відбиралися на відстанях 5, 10 і 15 метрів (рис. 3, А). Це уможливлює простеження поступових змін морфологічних та фізико-хімічних властивостей забрудненого ґрунту із віддаленням від епіцентру вибуху.

Наведена схема має забезпечити отримання репрезентативних даних про рівень мілітарного забруднення ґрунту дослідних ділянок важкими металами. Власне для польових робіт було передбачено визначити вже *in situ* 3 дослідні ділянки пробовідбору з орієнтовним розміром 40х40 м.

Локації відбору проб ґрунту на дослідних ділянках також мають бути експертно-визначеними. За такі локації було обрано: *1) центр вирви*. Планувалось відібрати по одній гніздовій пробі з вирви. Кожну таку пробу, як вже зазначалось, має бути утворено шляхом об'єднання 21 точкової проби, з яких 1 відбиралася у центрі вирви, а 20 – за умовним колом, побудованим на відстані 0,25 м від цього центра (рис. 3, В); *2) вершину бровки вирви*. Було передбачено відібрати 4 гніздові проби з кожної вирви, поєднаних зі сторонами світу (див. попередній текст). Точкові проби для кожної такої гніздової проби (21 пробу) має бути відібрано з кожної з чотирьох умовних дуг, утворених вершиною бровки вирви. Тобто мова має йти про північну, східну, південну та західну дуги з віднесенням однієї точкової проби до середини кожної дуги, а ще 20 точкових проб – по 10 в обидва боки від такої середини (рис. 4, А); 3) *локації в межах дослідної ділянки поза вирвою*. Було заплановано відібрати методом «конверта» за сторонами світу по 3 гніздові проби ґрунту для кожної сторони. Перша з цих проб розміщується за 5 метрів від перетнутої лінією обраного напрямку вершини бровки вирви, наступна – ще за 5 метрів і третя – ще за 5 метрів від попередньої (див. рис. 3, А). За таких умов на кожній дослідній ділянці було передбачено відібрати методом «конверта» 12 гніздових проб ґрунту. Схему відбору гніздових проб за цим методом подано на рис. 4, В. Згідно з останнім горизонтальна та вертикальна осі «конверта», проведені через перетин діагоналей «конверта» як квадрата зі сторонами по 0,5 м, ділять ці сторони навпіл. Ці осі при розміщенні «конвертів» за схемою рис. 3, А, відповідно збігаються з напрямками сторін світу: вертикальна з напрямком «північ – південь», а горизонтальна – з напрямком «схід – захід». Одиничні проби для отримання гніздової проби передбачалось відбирати в чотирьох кутах «конверта», в його центрі, який збігається з центроїдом цієї фігури, а також на сторонах та діагоналях «конверта» (рис. 4, В); 4) *локації фонових проб ґрунту*. Було також передбачено відібрати методом «конверта» дві

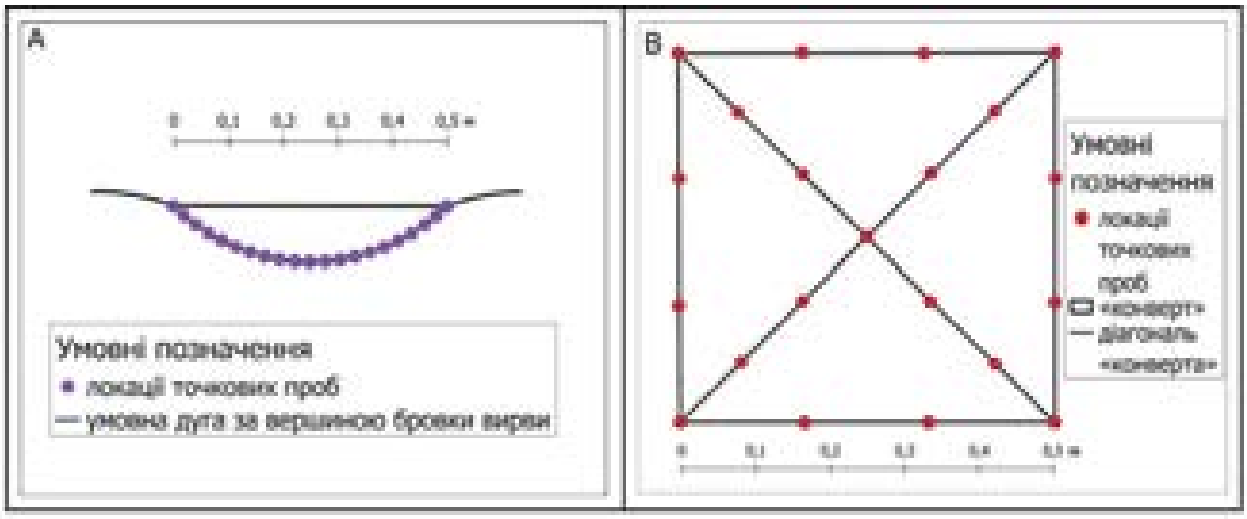


Рис. 4. Схема відбору точкових проб: для гніздової проби, розміщеної на кожній умовній дузі, утвореній вершиною бровки вирви (А) та для гніздової проби в межах дослідної ділянки поза вирвою (В) /
Fig. 4. Scheme of point sampling: for a cluster sample placed on each conventional arc formed by the top of the crater edge (A) and for cluster sample within the research plot outside the crater (B)

фонові гніздові проби з поверхні орного шару та з прикопки глибиною 0,45 м.

Отже, згідно з розробленою Стратегією, яка у цілому за змістом відповідає ймовірнісному систематичному геопросторовому скринінговому пробовідбору ґрунту [42, 43], було заплановано вивчити три дослідні ділянки з вирвами. На кожній з них доцільно відібрати 17 гніздових проб, а саме: 1 пробу з центру вирви, 4 з вершини бровки вирви та 12 з локацій в межах дослідної ділянки поза вирвою. Таким чином, за наявності трьох дослідних ділянок і зважаючи на 2 фонових пробовідбори, загалом було передбачено відбір 53 гніздових проб.

Апробацію розробленої Стратегії група дослідників КНУ імені Тараса Шевченка провела під час польових досліджень ґрунтів агроландшафту 5 вересня 2025 р. за бездощових погодних умов.

Дослідні ділянки характеризувалися рівнинним рельєфом, пригніченим рослинним покривом, ознаками вигорання та слідами розпорошених твердих запалювалювальних речовин, які було зафіксовано безпосередньо на поверхні ґрунту. Незначна кількість опадів, яка характерна для регіону дослідження, призвела до формування поверхневої кірки товщиною до 1 см на поверхні досліджуваних чорноземів важкосуглинкових, що додатково уповільнило їхній промивний режим і дію еолових процесів. Тимчасові водні потоки та ерозійні форми, які вони можуть спричинювати, на дослідних ділянках не спостерігалися. Також не було зафіксовано механічної обробки ґрунту цих ділянок на кшталт оранки, боронування тощо.

Агроландшафт, в межах якого вже *in situ* було визначено 3 дослідні ділянки для відбору гніздових проб ґрунту, був щільно мілітарно пошкодженим, зокрема внаслідок бомбтурбацій НАР С-8. В агроландшафті спостерігалися вирви від знешкоджених таких ракет, подібні між собою за морфологічною будовою. Останнє і правило за критерій остаточного вибору дослідних ділянок, з площею кожної близько 1600 м^2, і маршрутного ходу польового дослідження, який становив 332 м (рис. 5). Експертно-польовий огляд дослідних ділянок підтвердив коректність попередньо прийнятого рішення при обґрунтуванні Стратегії щодо відбирання гніздових проб приповерхнево на глибині 1-5 см в орному шарі ґрунту. З одного боку, реальний стан дослідних ділянок засвідчив низьку ймовірність низхідної міграції важких металів, а отже і відповідного перерозподілу потенційних забруднень, спричинених мілітарним впливом. З іншого боку, доцільність зазначеної глибини пробовідбору було зумовлено також невеликим часовим проміжком від моменту знешкодження ракет до моменту відбирання проб. За інформацією фахівців з групи розмінування таке знешкодження відбувалося тротиловим зарядом у 400 г у вирві К1 і К3 29.07.2025, а у вирві К2 16.08.2025 (рис. 5).

У цілому, як і планувалося, було досліджено три ділянки з вирвами діаметром 1,4 м кожна та глибиною від вершини бровки вирви 0,454 м (вирва К1), 0,625 м (вирва К2) та 0,515 м (вирва К3) (рис. 5).

Локації гніздового відбору проб ґрунту були географічно прив'язані до цифрової картографічної основи за допомогою GPS-приймача Garmin GPSMAP 67 та координатно ідентифіковані на місцевості в системі координат UTM. Така прив'язка та ідентифікація забезпечила можливість наступного створення цифрових карт дослідження та, за потреби продовження

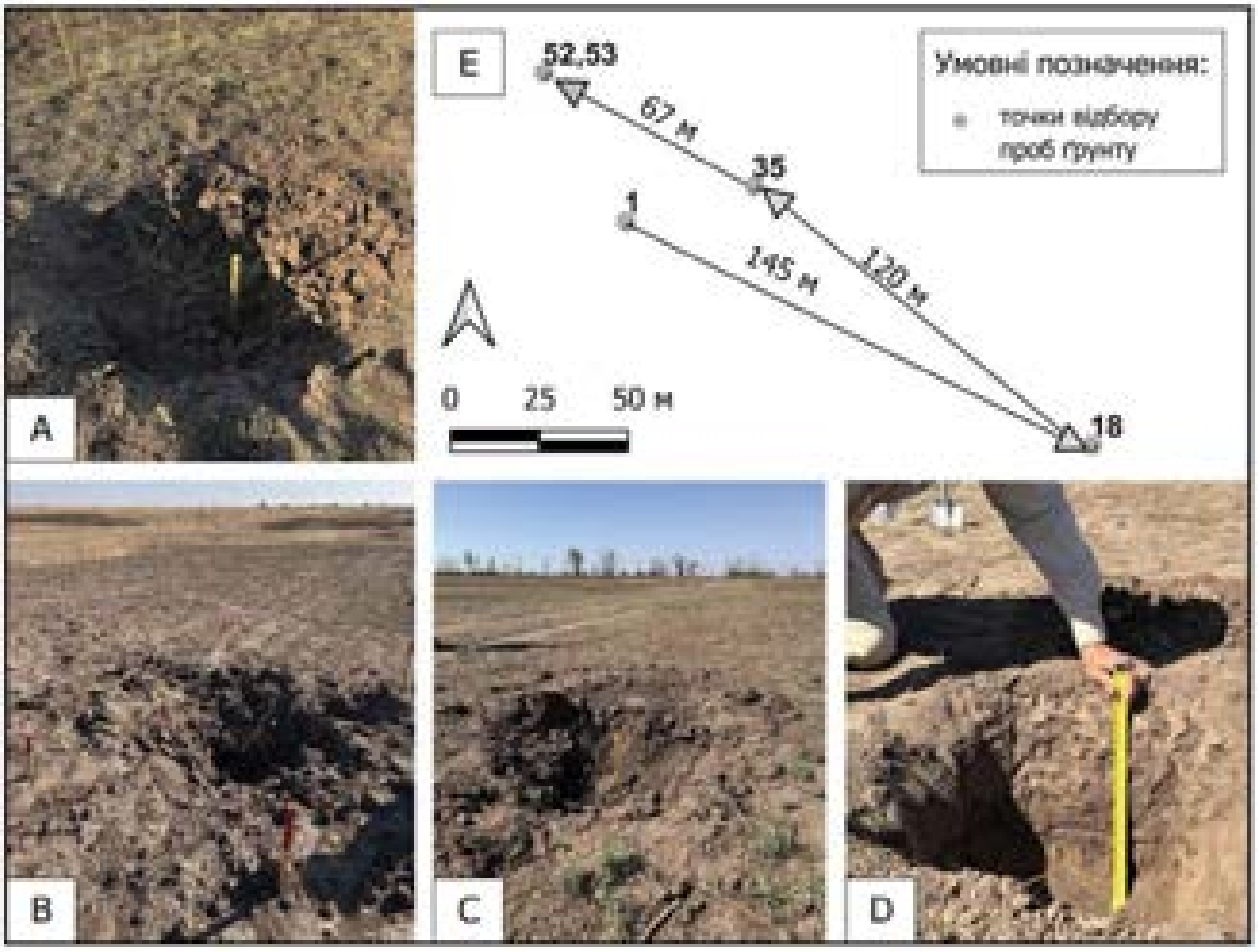


Рис. 5. Вирви обраних дослідних ділянок: A) першої (K1); B) другої (K2); C) третьої (K3) та D) локація фонової проби ґрунту. E) схема маршрутного ходу польового дослідження 2025-09-05 /
Fig. 5. Craters of selected research plots: A) first (K1); B) second (K2); C) third (K3) and D) location of baseline soil sample. E) scheme of field research route run 2025-09-05

останнього, повторного знаходження локацій відбору проб.

Для маркування відібраних гніздових проб ґрунтів було застосовано етикетки для ідентифікації відібраного матеріалу із зазначенням відомостей, передбачених стандартами [27, 28]. Також, контролювалась вимога про те, що точки відбору проб мають знаходитися більше ніж в 50 м від доріг, лісосмуг і складів органічних і мінеральних добрив. При відборі гніздових проб їхнє вторинне забруднення було виключене. Це було досягнуто за рахунок використання двох комплектів польових інструментів.

У польових умовах велась також окрема експлікаційна відомість (табл. 1).

У результаті польових досліджень було відібрано заплановані 51 гніздова проба ґрунтів на 3-х дослідних ділянках з вирвами та 2 таких фонових проби. Тобто у цілому було відібрано 53 гніздових проби як агрегація 1113 точкових проб ґрунту (рис. 6).

Вага кожної відібраної гніздової проби ґрунту становила близько 1 кг, зважаючи на те, що з ві-

Таблиця 1 / Table 1

Експлікація кластерних проб ґрунту /Cluster sampling explication

№	код	метод	№	код	метод	№	код	метод	№	код	метод
1	K1-D	за колом	14	K1-Б4-W	лінійно	27	K2-Б4-W	лінійно	40	K3-Б2-S	лінійно
2	K1-Б1-N	лінійно	15	K1-5-W	«конверт»	28	K2-5-W	«конверт»	41	K3-5-S	«конверт»
3	K1-5-N	«конверт»	16	K1-10-W	«конверт»	29	K2-10-W	«конверт»	42	K3-10-S	«конверт»
4	K1-10-N	«конверт»	17	K1-15-W	«конверт»	30	K2-15-W	«конверт»	43	K3-15-S	«конверт»
5	K1-15-N	«конверт»	18	K2-D	за колом	31	K2-Б3-E	лінійно	44	K3-Б3-E	лінійно
6	K1-Б2-S	лінійно	19	K2-Б1-N	лінійно	32	K2-5-E	«конверт»	45	K3-5-E	«конверт»
7	K1-5-S	«конверт»	20	K2-5-N	«конверт»	33	K2-10-E	«конверт»	46	K3-10-E	«конверт»
8	K1-10-S	«конверт»	21	K2-10-N	«конверт»	34	K2-15-E	«конверт»	47	K3-15-E	«конверт»

Продовження Таблиці1 / Continuation Table 1

9	К1-15-S	«конверт»	22	К2-15-N	«конверт»	35	К3-D	за колом	48	К3-Б4-W	лінійно
10	К1-Б3-E	лінійно	23	К2-Б2-S	лінійно	36	К3-Б1-N	лінійно	49	К3-5-W	«конверт»
11	К1-5-E	«конверт»	24	К2-5-S	«конверт»	37	К3-5-N	«конверт»	50	К3-10-W	«конверт»
12	К1-10-E	«конверт»	25	К2-10-S	«конверт»	38	К3-10-N	«конверт»	51	К3-15-W	«конверт»
13	К1-15-E	«конверт»	26	К2-15-S	«конверт»	39	К3-15-N	«конверт»	52	Fon ho	«конверт»
									53	Fon He	«конверт»

дібраних проб було видалено візуально помітні рештки рослинності, елементи ґрунтової фауни та сторонні домішки, зокрема уламки боєприпасів. Пакування проб здійснювалось в поліетиленові пакети. Запакована в пакет гніздова проба ґрунту розміщувалась ще в одному додатковому пакеті разом з маркувальною етикеткою.

Усі 53 гніздові проби ґрунту було доставлено до навчально-наукової лабораторії екології ландшафту кафедри фізичної географії та геоекології LandscapeLabKNU географічного факультету КНУ імені Тараса Шевченка. Відібрані проби було висушено в сухих і добре провітрюваних приміщеннях протягом 14 днів за температури не нижче +18°С та підготовлено для формування зразків для лабораторного дослідження.

Висновки

Польові дослідження мілітарного забруднення ґрунтів агроландшафтів є актуальними і важливими з точки зору обґрунтування, розробки та апробації відповідної Стратегії відбирання проб як етапу Програми таких досліджень. Унікальність презентованої процедури польових досліджень і результатів зумовлено застосуванням методології ландшафтно-екологічного аналізу та агроландшафтом як об'єктом, обраним для досліджень. Ґрунти є визначальним складником агроландшафту, однак сценарії поведінки забрудників в довкіллі, а саме первинний та вторинний їхній розподіл, зумовлено властивостями цілісних, відособлених та відносно однорідних природно-виробничих систем. До прикладу, досліджуваний агроландшафт 2 за рис. 2 , що розташовано в ІІ-му ландшафтному ярусі позиційно-динамічного району, є іншим та відмінним від агроландшафту 1 на рис. 2 з такою ж самою агровиробничою групою ґрунтів але в умовах І-го ландшафтного ярусу. А отже риси формування і прояву агроландшафтів з однаковою агровиробничою групою ґрунтів, розміщених в різних по-

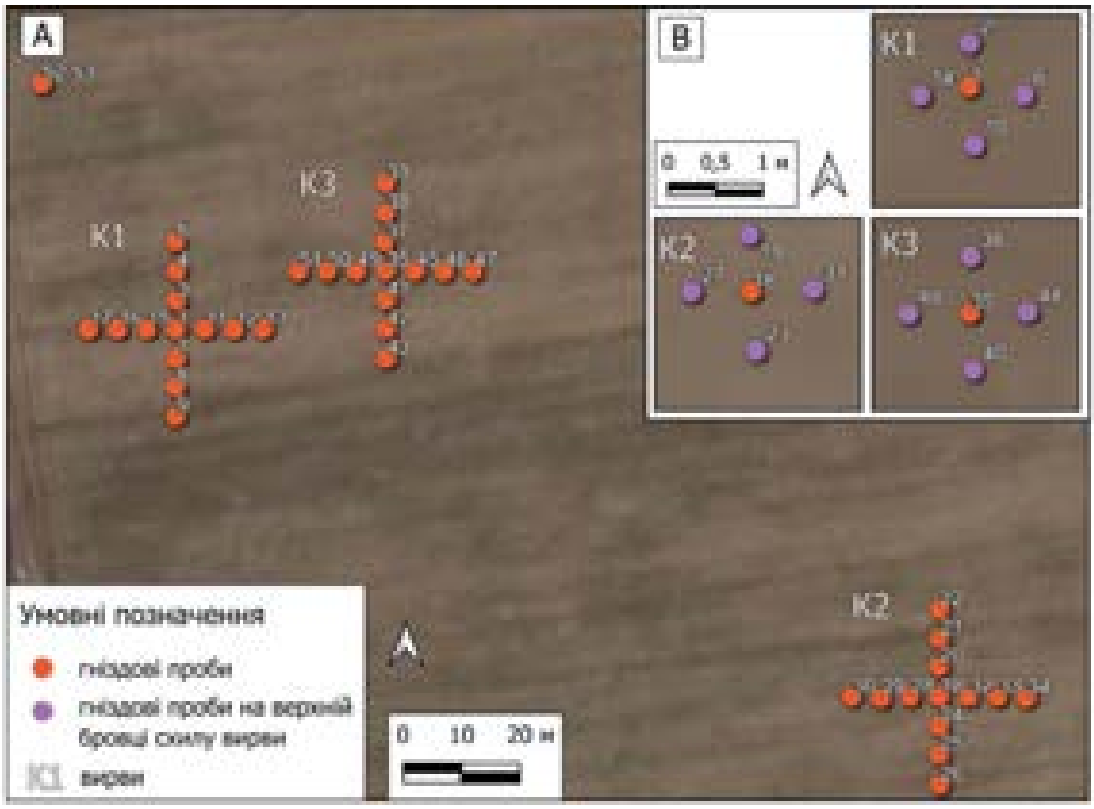


Рис. 6. Дослідні ділянки та локації відбирання проб ґрунту
Fig. 6. Research plots and soil sampling locations

зиційно-динамічних і геоморфологічних умовах, суттєво різняться за складом, напрямком та інтенсивністю всіх фізико-хімічних процесів. Для проведеного дослідження одна і та ж агровиробнича група ґрунтів притаманна агроландшафтам як денудаційних так і акумулятивних низовин, які і зумовлюють її диференціацію на відповідні агроландшафти та різні об'єкти досліджень.

Стратегія відбирання проб ґрунтів на обраних дослідних ділянках агроландшафту визначалась результатами аналізу досвіду подібного пробовідбору ґрунтів, які зазнали бомбтурбацій, камеральними передпольовими узагальненнями всіх передумов польових робіт *in situ* та експертно-аналітичними рішеннями в процесі польового дослідження.

Отримані результати досліджень мілітарних забруднень важкими металами ґрунтів агроландшафту 2 на рис. 2, спричинених бомбтурбаціями НАР С-8, може бути екстрапольовано на територію всього II-го ландшафтного ярусу позиційно-динамічного району для таких самих агроландшафтів з аналогічними мілітарними чинниками їхнього стану. На території Шевченківської об'єднаної територіальної громади площа агроландшафтів для потенційної екстраполяції результатів проведеного дослідження становить 11,52 км².

Таким чином, новизна проведених розвідок визначається обґрунтованою та апробованою методикою, об'єктом і Стратегією відбирання проб при польовому дослідженні мілітарного забруднення ґрунтів агроландшафтів, спричинених бомбтурбаціями НАР С-8. Результати дослідження є релевантними для запровадження ефективних програм дослідження й аналізу стану ґрунтів і використання цих результатів при розробці уніфікованої на рівні держави процедури вивчення і оцінки стану забруднених війною ґрунтів для їхнього відновлення.

Внесок авторів: всі автори зробили рівний внесок у цю роботу
Конфлікт інтересів: автори повідомляють про відсутність конфлікту інтересів
Декларація про використання генеративного штучного інтелекту: автор підтверджує, що під час підготовки рукопису не використовувалися інструменти штучного інтелекту.

Authors Contribution: All authors have contributed equally to this work
Conflict of Interest: The authors declare no conflict of interest

Declaration of use of generative artificial intelligence: The author confirms that no AI tools were used during the preparation of the manuscript.

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Field research on military contamination for soils of agricultural landscapes with heavy metals

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ABSTRACT

The aim of the research was to study the agrolandscape diversity of the territory through landscape-ecological analysis and substantiation, development and pilot testing of a Strategy for sampling soils of agrolandscapes militarily altered by massive bomb-turbation with uncontrollable aircraft missiles (UAM) S-8 for laboratory determination of extent for their contamination with heavy metals.

Methods. The methods of landscape-ecological analysis were used, namely those related to the analysis of nature management and landscape planning and design, anthropization of landscapes, agroecology, landscape geochemistry, ecological-geochemical studies of heavy metal migration in agricultural landscapes, landscape-ecological geospatial analysis and modeling. The methodology of geospatial analysis using the GIS tools ArcGIS and QGIS and the procedure of probabilistic systematic geospatial screening of soil sampling were also applied. The object of the field research was the simulated landscape tiers and strips of positional-dynamic structure and the war-affected agro-landscapes of the Shevchenkivska United Territorial Community (UTC) of the Mykolaiv region in Ukraine.

Results. The scientific-applied potential of the landscape-ecological analysis methodology for substantiating the strategy of field research on military soil contamination of agricultural landscapes with heavy metals was considered. The positional-dynamic landscape territorial structure, simulated using tools for open digital data geospatial analysis, is defined as the basis for synthesizing information on the agrolandscape diversity of territories. The results of the testing for the developed strategy of field research on soils of agricultural landscapes, obtained during field research in the Shevchenkivska UTC, are presented.

The uniqueness of the proposed field research procedure and results is due to the application of the methodology of landscape-ecological analysis and the agrolandscape as an object selected for research.

The soil sampling strategy at selected research sites of the agrolandscape was determined by the results of the analysis for experience with similar sampling of soils that had been subjected to bomb-turbation, by office-based pre-field generalizations of all prerequisites for *in situ* work, and by expert-analytical decisions during the field research.

The obtained results of research on military contamination of soils with heavy metals for the selected agrolandscape can be extrapolated to the territory of the entire studied landscape tier of the positional-dynamic area for the same agrolandscapes with similar military factors of their condition.

Conclusions. The novelty of the conducted investigations is determined by the substantiated and tested methodology, object and sampling strategy for field research of military contamination of agricultural landscapes soils. The research results are relevant for the implementation of effective research programs and analysis of soil condition and the use of these results in the development of a unified state-level procedure for studying and assessing the condition of war-contaminated soils for their recovery.

ARTICLE INFO

Manuscript received
2 January 2026

Revised manuscript received
7 February 2026

Manuscript accepted
25 May 2026

Available online
30 May 2026

Keywords:

military contamination, heavy metals, landscape-ecological analysis, geospatial analysis, positional-dynamic conditions, soil field research strategy, agrolandscape, extrapolation of results, soil recovery.

In cites: Hryhorii Denysyk, Serhii Zapototskyi, Viktor Samoilenko, Liudmyla Bilous, Yevhen Tsyhanok, Kostiantyn Hura, Oleksandr Halahan, Mariia Kandii, Natalia Nahorna (2026). Field research on military contamination for soils of agricultural landscapes with heavy metal. *Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology*, (64), 369–382. https://doi.org/10.26565/2410-7360-2026-64-28 [In Ukrainian]

https://doi.org/10.26565/2410-7360-2026-64-29

УДК 504.064.36:556.114.6

Моніторинг важких металів як основа оцінки якості вод річки Південний Буг

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АНОТАЦІЯ

У статті представлено результати комплексних досліджень хімічного складу річкових вод басейну р. Південний Буг, що формуються під впливом поєднання природних геохімічних процесів та антропогенного навантаження. Будучи головною водною артерією центрального регіону, він виконує роль ключового джерела господарсько-питного водопостачання та виступає стратегічним ресурсом для забезпечення енергетичної та продовольчої безпеки держави. Встановлено, що підземні води, які акумулюють продукти руйнування кристалічних порід Українського щита, є основним джерелом живлення річкової системи, а різна мінералізація водоносних горизонтів зумовлює просторову неоднорідність складу. Детальний аналіз гідрохімічних показників дозволив ідентифікувати зони найбільш інтенсивного техногенного впливу в межах басейну. Особлива увага приділена ролі водневого показника pH як ключового регулятора розчинності, міграції та токсичності важких металів. Сезонні коливання pH (6,5–8,76) відображають вплив температурних та біологічних процесів, що визначають динаміку кислотно-лужного балансу. Дослідження концентрацій заліза, міді та марганцю виявило різну сезонну поведінку. У період весняної повені концентрації $Fe_{заг}$ коливалися в межах 0,23–0,36 мг/дм³, що перевищує нормативне значення. У літньо-осінню межень відзначається певне зниження концентрацій заліза, проте вони залишаються досить варіативними – від 0,2 до 0,31мг/дм³. Аналогічна тенденція простежується і в зимову межень. Вміст міді залишається відносно стабільним (0,0013–0,095 мг/дм³) завдяки здатності зв'язуватися з органічною речовиною. Вміст марганцю в річковій воді демонструє перевищення нормативів (досягаючи рівня 0,12 мг/дм³) унаслідок природних і антропогенних факторів, а також це може бути пов'язано з процесами мобілізації металів із донних відкладів унаслідок зміни окисно-відновного потенціалу та температурного режиму. Встановлено, що інтенсивність вимивання металів корелює з інтенсивністю атмосферних опадів та рівнем сільськогосподарського освоєння водозборів. Отримані результати підтверджують взаємозв'язок між pH та концентраціями металів, що визначає якість води та екологічну безпеку річкових екосистем. Виявлені закономірності просторово-часового розподілу

ІНФОРМАЦІЯ ПРО СТАТТЮ :

Рукопис надійшов
11 лютого 2026

Отримано після рецензування
17 березня 2026

Затверджено до друку
25 травня 2026

Опубліковано онлайн
30 травня 2026

Ключові слова:

екологічний моніторинг, забруднення річкових вод, водневий показник pH, забруднення важкими металами, сезонна динаміка забруднення, гідроекосистеми, екологічна безпека, нормативне значення, антропогенне навантаження, річкові басейни.

Як цитувати : Залізняк Яна, Сонько Сергій, Василенко Ольга, Балабак Олександр, Балабак Алла, Гурський Ігор (2026). Моніторинг важких металів як основа оцінки якості вод річки Південний Буг. *Вісник Харківського національного університету імені В.Н. Каразіна Серія «Геологія. Географія. Екологія»*, (64), 383–394. https://doi.org/10.26565/2410-7360-2026-64-29

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металів створюють наукове підґрунтя для розробки природоохоронних заходів, спрямованих на зниження негативного впливу антропогенних чинників, запобігання вторинному забрудненню та забезпечення сталого функціонування басейну Південного Бугу.

Вступ

Забруднення поверхневих і підземних вод високими концентраціями важких металів є глобальним екологічним викликом, що потребує комплексного вирішення на міжнародному рівні. Саме тому у 2015 році Організація Об'єднаних Націй ухвалила Глобальні цілі сталого розвитку, спрямовані на подолання бідності, захист планети та забезпечення процвітання до 2030 року. Серед них ключовою є Ціль 6: «Чиста вода та належні санітарні умови», яка акцентує увагу на необхідності забезпечення доступності безпечної води та зменшення антропогенного навантаження на водні ресурси [1].

У цьому контексті особливого значення набуває дослідження стану річкових систем України, зокрема басейну р. Південний Буг, який є важливим джерелом водопостачання та має стратегічне значення для регіонального розвитку. Територія басейну річки має високий рівень господарського освоєння. Це один із найрозвиненіших аграрних регіонів України, що одночасно має значний рівень промислового виробництва. Сільськогосподарські угіддя становлять 81% площі басейну в межах області.

Додатково слід враховувати, що річки сходу та півдня України зазнали значного забруднення внаслідок воєнних дій, які супроводжуються руйнуванням промислових об'єктів, інфраструктури та систем водопостачання. Це призводить до потрапляння у водні екосистеми токсичних речовин, включаючи важкі метали, нафтопродукти та інші небезпечні сполуки. У таких умовах особливо важливо зберегти відносно стабільний екологічний стан річок центральної частини країни, зокрема Південного Бугу, який може відігравати роль резервного джерела водних ресурсів та підтримувати екологічну рівновагу регіону.

Проблема забруднення вод Південного Бугу важкими металами відображає загальносвітові тенденції. У всьому світі багато дослідників повідомляють про забруднення річкових басейнів важкими металами, що підтверджує високий рівень антропогенних скидів у басейни річок, які забруднюють як воду, так і відклади. Академічні дослідження підтверджують, що важкі метали у водних екосистемах спричиняють комплексні хімічні та біологічні зміни, які порушують функціонування природних процесів [2; 3]. Вони здатні переходити у розчинну форму залежно від кислотно–лужного балансу, що підвищує їхню мобільність та токсичність для гідробіонтів [4]. У результаті відбувається порушення метаболічних процесів у риб та безхребетних, зниження біорізноманіття та деградація екосистем [5]. Дослідження, проведене дослідниками [6], показало, що навіть відносно низькі концентрації металів у річкових системах міст створюють значні ризики для водної біоти та населення, яке використовує ці ресурси для питного водопостачання.

Дослідження, які містять розробки теоретичних основ і практичних методів для визначення та оцінювання антропогенного навантаження, зокрема вмісту важких металів у поверхневих водах басейну, і стійкості річкових басейнів, представлені і у роботах вітчизняних вчених. Зокрема, у працях М. М. Ганущак [7, 8] охарактеризовано якість поверхневих вод, яка прямо залежить від ступеня антропогенної змінності басейнової системи. Науковець О. М. Крайнюков описує використання різних методик для оцінювання екологічного стану поверхневих вод та оцінювання різних наслідків їх забруднення, а також і їх токсикологічного стану [9–11]. Антоняк Г. Л. у своїх напрацюваннях зазначає вплив важких металів на водних мешканців – гідро біонтів [12]. Гуменюк Г. Б. у своїй науковій роботі [13] здійснив порівняльну характеристику розподілу важких металів у гідроекосистемах різного типу. Отже, незважаючи на значний масив вітчизняних досліджень, присвячених оцінці антропогенного навантаження та забруднення басейну Південного Бугу, специфіка забруднення поверхневих вод важкими металами залишається актуальним і відкритим для вивчення напрямком.

Небезпека полягає також у тому, що важкі метали мають здатність накопичуватися у донних відкладах, утворюючи своєрідні «резервуари» забруднення [14]. За зміни гідрохімічних умов вони можуть повторно переходити у водну товщу, спричиняючи вторинне забруднення. Це явище ускладнює процеси очищення та робить забруднення довготривалим і стійким. Як зазначають автори [15], поєднання важких металів із іншими забруднювачами, зокрема мікропластиком, створює синергетичний ефект, що посилює токсичність і підвищує ризики для здоров'я людини, включаючи канцерогенні та нейротоксичні наслідки.

З точки зору суспільного здоров'я, забруднені важкими металами річкові води становлять небезпеку через їхнє використання у системах питного водопостачання [16] та сільському господарстві [17]. Метали можуть потрапляти у харчові ланцюги, акумулюючись у рослинах і тваринах, що призводить до хронічного впливу на організм людини. Це підтверджено низкою



Рис. 1. Карта мережі спостережень за показниками гідрологічного та гідрохімічного режимів водотоків у межах басейну Південного Бугу (нумерація згідно з переліком досліджуваних річок) /
Fig. 1. Map of the observation network for hydrological and hydrochemical indicators of watercourses within the Southern Bug River basin (numbering according to the list of studied rivers)

міжнародних наукових публікацій, які аналізують біоакумуляцію та токсичні наслідки для здоров'я [1; 18; 19].

З огляду на наведені дані, проблема забруднення річкових вод важкими металами має не лише локальний, а й глобальний характер, що підтверджується численними міжнародними дослідженнями. У цьому контексті критично важливим є удосконалення систематичного моніторингу якості води. Відповідно до Статті 8 Водної рамкової директиви ЄС (Директива 2000/60/ЄС) [20], програми моніторингу повинні забезпечувати узгоджений та всебічний огляд екологічного та хімічного стану поверхневих вод у кожному річковому басейні та дозволяти класифікувати масиви вод згідно з Додатком V до ВРД [20]. Тому дослідження були спрямовані на отримання інформації про стан річкового басейну та якість води для розроблення найбільш раціональних, економічно вигідних і екологічно безпечних шляхів господарського використання території басейну Південного Бугу.

Методи. Геоморфологічне розташування басейну Південного Бугу є специфічним, оскільки він має витягнуту орієнтацію з північного заходу на південний схід в межах Правобережної України. Ландшафт досліджуваного регіону є типовим Східноєвропейської рівнинної ландшафтної країни. Протяжність річки складає 806 км і вона є однією з провідних водних систем України. Маючи площу водозбору 63 700 км^2, басейн річки межує з басейном р. Дністра на заході, а на півночі та сході – з басейном Дніпра.

Територіально басейн Південного Бугу охоплює сім областей України, серед яких Вінницька займає позицію лідерів, оскільки охоплює 25,7% площі басейну. Гідрографічна мережа басейну вирізняється розгалуженістю та значною кількістю приток. Так як лівобережна частина Південного Бугу зазнає найінтенсивнішого антропогенного впливу, через велике зосередження промислових підприємств та фермерських господарств, то для проведення моніторингу нами було обрано саме ліві притоки річки в межах Вінницької області. Дослідження проводилося за басейновим підходом, що дало змогу виявити закономірність збільшення вмісту забруднюючих речовин у воді від північних до південних районів.

Дослідження проводили у 2023–2025 роках. Гідрохімічна база даних була сформована за 10 пунктами спостережень (рис 1).

Нижче наведено перелік досліджуваних річок з координатами місць відбору проб поверхневих вод (табл. 1).

Збір та систематизація гідрохімічних показників проводилися з урахуванням сезонної періодичності: періоду повені та меженних періодів (зимового та літньо-осіннього). Такий розподіл дозволив ідентифікувати однорідні групи даних, що характеризують відмінності у механізмах надходження та трансформації хімічних речовин у річкові води в різні фази гідрологічного року.

Точки відбору проб води визначалися з урахуванням розташування базису ерозії річкових систем, оскільки наближення приток до головної артерії – Південного Бугу – та особливості

Таблиця 1 / Table 1

Досліджувані річки з координатами точок відбору проб / Studied rivers and coordinates of sampling points

№	Річка	Географічні координати / точок відбору проб води
1	Снивода	Витік: 49.673008, 28.171597
		Рибгосп (с. Пиків): 49.56136715440914
		Гирло: 49.478289, 28.330459
2	Десна	Витік: 49.429624, 28.676661
		СФГ «Лоза» (с. Лозівка): 49.489139, 28.824451
		Гирло: 49.321439, 28.497152
3	Соб	Витік: 49°21′48″, 29°05′25″
		Підприємства (м. Іллінці): 49.112181, 29.208017
		Гирло: 48°40′36″, 29°16′37″
4	Удич	Витік: 48.649923, 29.963576
		Відбір вод від м. Теплик (с. Пологи): 48.576810, 29.725821
		Гирло: 48°29′32″ , 29°40′09″
5	Устя	Витік: 48°51′20″, 28°59′41″
		Південний схід від м. Немирів: 48.952860, 28.865361
		Гирло: 48.855153, 28.994757
6	Рудка	Витік: 48.889941, 29.185234
		ПСП «Мрія» (с. Косанове): 48.836050, 29.194402
		Гирло: 48°48′45″, 29°09′02″
7	Південний Буг (м. Вінниця)	49.278259, 28.469878 49.190378, 28.440831 49.273676, 28.470678 49.191685, 28.455910 49.231165, 28.483670
8	Південний Буг (м. Ладижин)	48.714173, 29.173393 48.672926, 29.281706 48.710064, 29.224926 48.682016, 29.265720
9	Південний Буг (м. Хмільник)	49.556706, 27.912617 49.548063, 27.958469 49.537721, 27.976928
10	Південний Буг (с. Ставки)	48.377200, 29.741288 48.372131, 29.774094 48.363697, 29.800475

сформованого ними рельєфу сприяють зростанню концентрації забруднюючих речовин. Для отримання порівняльних характеристик забір води проводився у ключових створах: біля витоку та в гирловій частині кожної досліджуваної річки, а також поблизу можливих об'єктів, які спричиняють забрудненню (промислові підприємства, фермерські господарства тощо).

Польові дослідження виконувались згідно «Методики комплексних польових географічних досліджень» [21]. Визначення вмісту важких металів у воді виконувались у лабораторії «УМАНЬВОДОКАНАЛ». Нормативні значення важких металів, якими ми керувалися, використані з джерела [22].

Обговорення результатів. Аналізуючи умови формування гідрохімічного режиму в басейні р. Південного Бугу, слід врахувати його розташування в межах Українського кристалічного щита. Впродовж року річки отримують основне живлення саме з підземних горизонтів, збагачених продуктами деструкції кристалічних порід та осадових пісків четвертинного періоду. У нижній течії, де басейн переходить у Причорноморську низовину, на склад води впливають вапнякові відклади та лесові породи. Тому зміна мінералізації підземних вод пов'язана з неоднорідністю кристалічної основи, що є ключовим фактором просторової мінливості гідрохімічних показників усієї річкової мережі.

Результати досліджень води на вміст важких металів є ключовим показником екологічного стану річкових екосистем, оскільки вони дозволяють не лише визначити фактичний рівень забруднення, але й простежити закономірності міграції та накопичення токсичних елементів у водному середовищі. Аналіз отриманих даних забезпечує можливість оцінити відповідність якості води санітарним нормам, виявити джерела антропогенного навантаження та визначити потенційні ризики для біоти й здоров'я населення. Таким чином, результати досліджень виступають науковим підґрунтям для розробки природоохоронних заходів, спрямованих на зниження негативного впливу важких металів та забезпечення сталого функціонування річкових систем.

Моніторинг водневого показника pH є необхідним елементом дослідження забруднення річкових вод важкими металами, оскільки саме кислотно-лужний баланс визначає їхню розчинність, міграцію та токсичність у водному середовищі. Зв'язок між рівнем водневого показника pH та вмістом металів у водах річок є одним із ключових чинників, що визначає якість водного середовища та його екологічну безпеку. Водневий показник виступає регулятором хімічної рівноваги у водних екосистемах, оскільки саме він визначає розчинність, міграцію та біодоступність металів. У кислих умовах, коли pH знижується, концентрація



Рис. 2–4. Водневий показник за різні періоди у досліджуваних річках
Fig. 2–4. pH values across different periods in the studied rivers

іонів водню зростає, що сприяє переходу багатьох металів у розчинну форму. Це стосується заліза, марганцю та міді які стають більш мобільними і токсичними для живих організмів. У нейтральному середовищі більшість металів перебуває у стані рівноваги між розчиненими та осадженими формами, тоді як у лужних умовах вони утворюють гідроксиди та карбонати, що випадають в осад і знижують їхню концентрацію у воді [23].

Таким чином, pH води визначає не лише хімічний склад річкових екосистем, але й рівень їхньої стійкості до антропогенного навантаження. У районах із підвищеною кислотністю, спричиненою кислотними дощами чи шахтними стоками, спостерігається зростання токсичності металів, що негативно впливає на рибу, безхребетних та водну рослинність. У лужних умовах ризик для біоти зменшується, проте виникає небезпека довготривалого накопичення металів у донних відкладах, які можуть слугувати джерелом вторинного забруднення [24]. Відповідно, моніторинг кислотно-лужного балансу води є необхідним елементом оцінки стану річкових екосистем, оскільки навіть незначні зміни pH здатні суттєво змінити доступність металів і вплинути на екологічну безпеку водних ресурсів.

Рівень водневого показника істотно впливає на формування якості води. Значення цього показника в досліджених річкових водах коливається від 6,5 до 8,5. При цьому спостерігають його зміни у різні сезони року, а саме в теплий період pH для більшості річок складає 7,31–8,76, у холодний – у межах 6,65–7,63. За рахунок даного показника зазначають ступінь агресивності води щодо вмісту металів, їх міграції тощо. У весняну повінь значення pH річкових вод басейну р. Південний Буг сягає меж 6,5–8,1 (рис. 2–4).

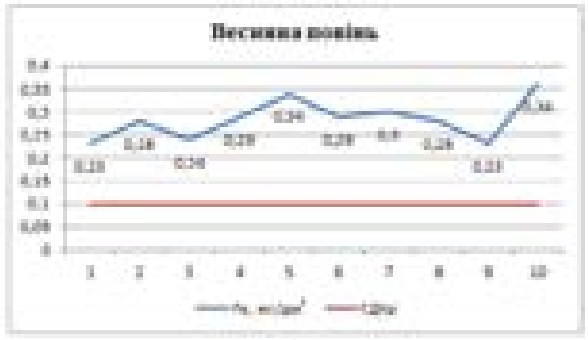
Результати проведених досліджень узгоджуються з висновками інших авторів [24; 25], які підтверджують, що водневий показник pH є динамічним параметром, чутливим до сезонних змін гідрологічних та кліматичних умов. Зокрема, встановлено, що температура води виступає одним із ключових чинників, який визначає інтенсивність хімічних та біологічних процесів у водному середовищі, а відтак безпосередньо впливає на рівень pH. У теплі періоди року, коли температура води зростає, активізуються процеси фотосинтезу та біологічного споживання вуглекислого газу, що може спричиняти підвищення pH у бік лужних значень. Натомість у холодний сезон зниження температури супроводжується зменшенням інтенсивності біологічних процесів та підвищенням розчинності газів, зокрема CO_2, що призводить до зсуву pH у кислий бік. Таким чином, сезонність виступає визначальним фактором у формуванні кислотно-лужного балансу річкових екосистем, а температура води є головним регулятором цих змін.

Крім того, дещо вищі значення можна побачити у тих частинах басейну р. Південного Бугу, де збільшені фотосинтетичні процеси, а саме у водосховищах, оскільки відбувається застій води. Найбільші підвищення pH спостерігаються у літньо-осінню межень до 8,76 у точці досліджень поблизу села Ставки, розташованого на кордоні Вінницької та Кіровоградської областей. Даний рівень водневого показника pH перевищує верхню межу гранично допустимих концентрацій. Отже, виникає низка небезпек для екосистеми та якості води. У таких умовах змінюється хімічна рівновага, що впливає на розчинність і доступність багатьох елементів. Більшість металів утворює нерозчинні гідроксиди та карбонати, які випадають в осад, проте це призводить до їхнього накопичення у донних відкладах і створює ризик вторинного забруднення при зміні гідрохімічних умов [26]. Також за свідченням [27] надмірна лужність також погіршує органолептичні властивості води, робить її непридатною для питного використання без попередньої обробки та може спричиняти утворення відкладень у водопровідних системах.

Вивчення вмісту заліза (Fe), міді (Cu) та марганцю (Mn) у річковій воді має важливе значення для оцінки екологічного стану водних екосистем та визначення рівня їхньої придатності для господарського використання. Ці метали належать до числа найбільш поширених природних компонентів гідросфери, проте їхня концентрація істотно залежить від геохімічних умов, рівня антропогенного навантаження та гідрологічних особливостей басейну. У малих кількостях вони виконують біологічно важливі функції, беручи участь у метаболізмі живих організмів, однак при перевищенні гранично допустимих концентрацій стають небезпечними полютантами, що негативно впливають на якість води та здоров'я населення [28; 29]. Тому, результати досліджень їх вмісту у річковій воді дозволяють простежити просторові та часові закономірності їхнього розподілу, виявити джерела забруднення та оцінити відповідність показників санітарним нормам. Вони є основою для формування висновків щодо екологічної безпеки водних ресурсів та розробки заходів з їхнього раціонального використання і охорони (рис. 5–7, 8–10, 11–13).

Вміст загального заліза у річкових водах басейну Південного Бугу демонструє чітку сезонну динаміку, що відображає як природні гідрологічні процеси, так і рівень антропогенного навантаження на річкову систему. У пе-





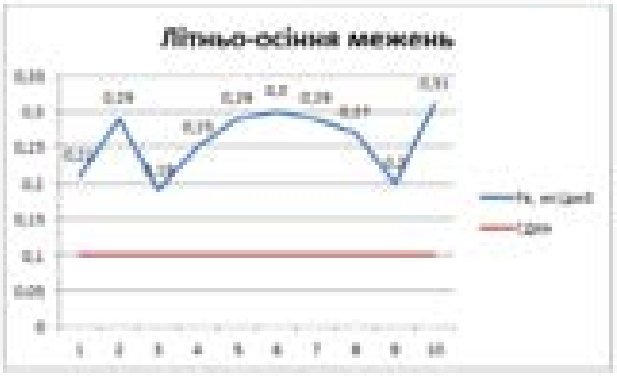
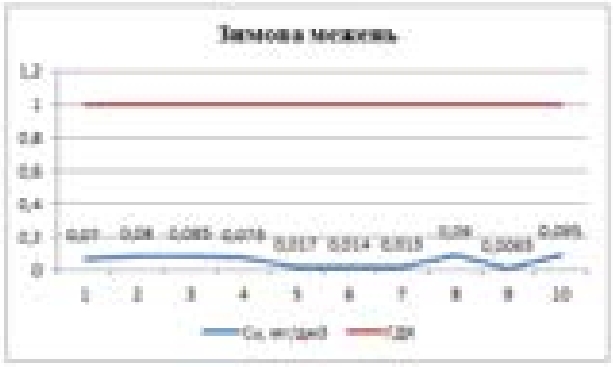


Рис. 5–7. Вміст $Fe_{заг}$ за різні періоди у досліджуваних річках
(де 1– р. Снивода, 2 – р. Десна, 3 – р. Соб, 4 – р. Удич, 5 – р. Устя, 6 – р. Рудка, 7 – р. Південний Буг (м. Вінниця), 8 – р. Південний Буг (м. Ладижин), 9 – р. Південний Буг (м. Хмільник), 10 – р. Південний Буг (с. Ставки)) /
Fig. 5–7. Total iron content ($Fetotal$) across different periods in the studied rivers
(where 1 – Snyvoda River, 2 – Desna River, 3 – Sob River, 4 – Udych River, 5 – Ustia River, 6 – Rudka River, 7 – Southern Bug River (Vinnytsia), 8 – Southern Bug River (Ladyzhyn), 9 – Southern Bug River (Khmilnyk), 10 – Southern Bug River (Stavky))



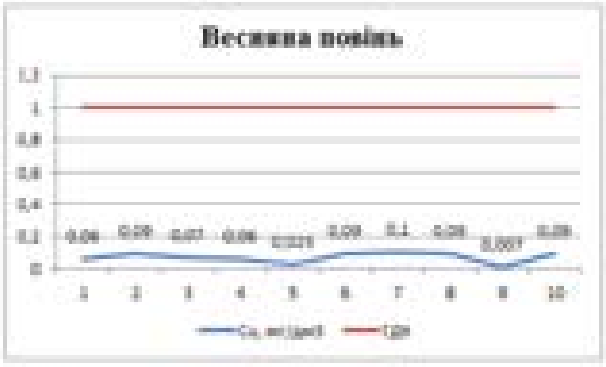




Рис. 8–10. Вміст Cu за різні періоди у досліджуваних річках
(де 1– р. Снивода, 2 – р. Десна, 3 – р. Соб, 4 – р. Удич, 5 – р. Устя, 6 – р. Рудка, 7 – р. Південний Буг (м. Вінниця), 8 – р. Південний Буг (м. Ладижин), 9 – р. Південний Буг (м. Хмільник), 10 – р. Південний Буг (с. Ставки)) /
Fig. 8–10. Copper (Cu) content across different periods in the studied rivers
(where 1 – Snyvoda River, 2 – Desna River, 3 – Sob River, 4 – Udych River, 5 – Ustia River, 6 – Rudka River, 7 – Southern Bug River (Vinnytsia), 8 – Southern Bug River (Ladyzhyn), 9 – Southern Bug River (Khmilnyk), 10 – Southern Bug River (Stavky))

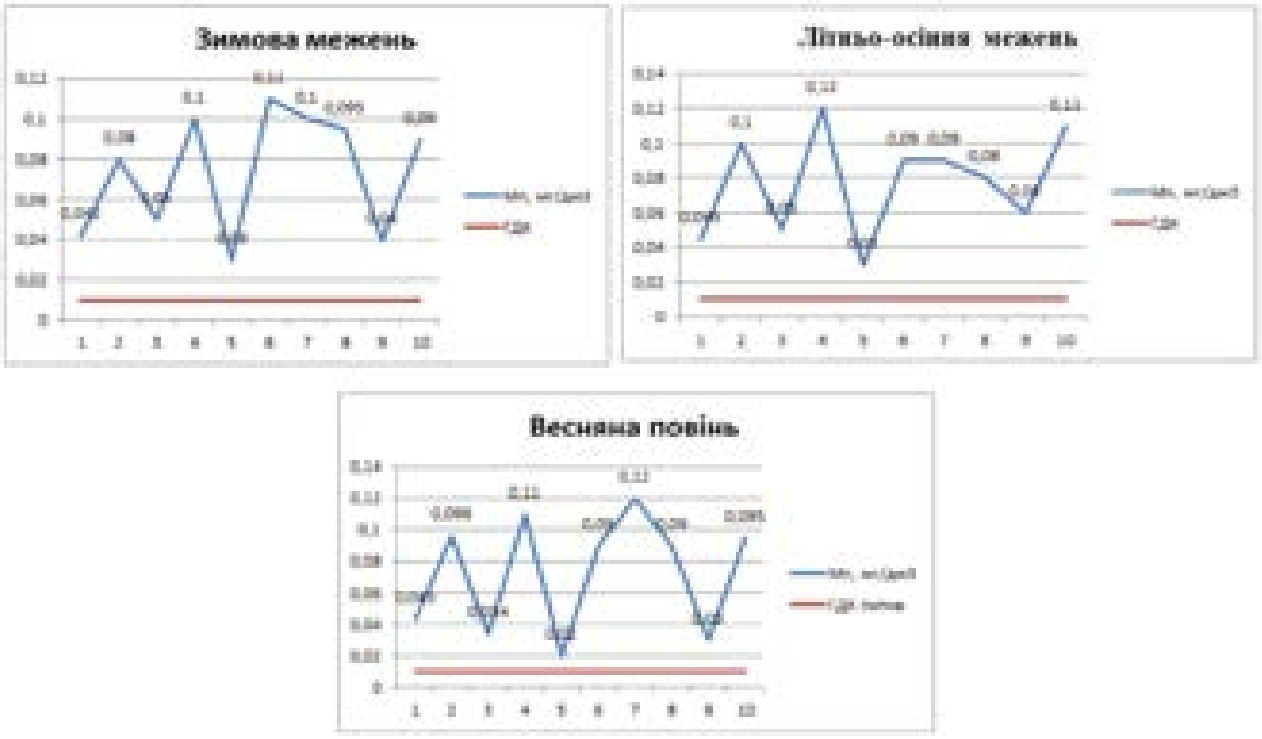


Рис. 11–13. Вміст Mn за різні періоди у досліджуваних річках
(де 1– р. Снивода, 2 – р. Десна, 3 – р. Соб, 4 – р. Удич, 5 – р. Устя, 6 – р. Рудка, 7 – р. Південний Буг (м. Вінниця), 8 – р. Південний Буг (м. Ладижин), 9 – р. Південний Буг (м. Хмільник), 10 – р. Південний Буг (с. Ставки)) /
Fig. 11–13. Manganese (Mn) content across different periods in the studied rivers
(where 1 – Snyvoda River, 2 – Desna River, 3 – Sob River, 4 – Udych River, 5 – Ustia River, 6 – Rudka River, 7 – Southern Bug River (Vinnytsia), 8 – Southern Bug River (Ladyzhyn), 9 – Southern Bug River (Khmilnyk), 10 – Southern Bug River (Stavky))

ріод весняної повені концентрації $Fe_{заг}$ коливалися в межах 0,23–0,36 мг/дм³, що перевищує гранично допустимі концентрації. Важливо підкреслити, що такі показники були зафіксовані практично на всіх пунктах спостережень, що свідчить про масштабність явища та його системний характер.

У літньо-осінню межень відзначається певне зниження концентрацій заліза, проте вони залишаються досить варіативними – від 0,2 до 0,31 мг/дм³. Аналогічна тенденція простежується і в зимову межень. У більшості пунктів спостережень концентрації заліза залишаються нижчими, однак у тих ділянках, де перевищення нормативного значення було зафіксоване раніше, показники залишаються стабільно високими – 0,25–0,31 мг/дм³. Це свідчить про стійкість джерел забруднення та можливе накопичення заліза у донних відкладах із подальшим його вивільненням у водну товщу за певних гідрохімічних умов. Результати досліджень [30] дозволяють стверджувати, що цими умовами можуть бути: зниження окисно-відновного потенціалу (анаеробні умови), коливаннях pH, наявность сульфідів та органічної речовини.

Сезонні коливання концентрацій міді (Cu) у водах річок басейну Південного Бугу (рис. 9–11) не виявили чітко вираженої динаміки, що свідчить про відносну стабільність цього показника в межах року. Зокрема, у період весняної повені вміст міді становив 0,004–0,09 мг/дм³, що відображає вплив інтенсивного поверхневого стоку та розбавлення водної маси талою водою. У літньо-осінню межень, а також у зимовий період концентрації Cu залишаються у близьких діапазонах – 0,0013–0,095 мг/дм³ як у притоках, так і в основному руслі річки. Відсутність значних сезонних змін може бути пояснена тим, що мідь належить до мікроелементів, які активно зв'язуються з органічною речовиною та мінеральними частинками, що забезпечує її відносну стабільність у водному середовищі.

Вміст марганцю (Mn) у водах басейну Південного Бугу та його приток, зокрема річки Удич, демонструє певні сезонні особливості. У період весняної повені та літньо-осінньої межені концентрації Mn дещо перевищували гранично допустимі концентрації (нормативного значення), досягаючи рівня 0,12 мг/дм³. Хоча ці показники не можна вважати критичними, вони свідчать про підвищене надходження марганцю у водне середовище під час інтенсивного поверхневого стоку та активізації процесів вилуговування з ґрунтів і гірських порід (рис. 12–14).

У літньо-осінню межень концентрація марганцю майже стабілізувалася і в більшості дослідних локацій не перевищувала норматив-

них значень, що пояснюється зменшенням водності річки, зниженням інтенсивності ерозійних процесів та більш рівномірним розподілом хімічних компонентів у водній товщі. Водночас у зимовий період у річці Удич було зафіксовано незначне перевищення нормативного значення (0,11 мг/дм^3), що може бути пов'язано з локальними геохімічними умовами, зокрема процесами мобілізації металів із донних відкладів унаслідок зміни окисно-відновного потенціалу та температурного режиму.

Основними джерелами надходження марганцю у поверхневі води є природні процеси вилуговування залізо-марганцевих руд та інших мінералів, що містять цей елемент. Крім того, вагомий внесок у формування його концентрацій здійснюють антропогенні фактори, зокрема стічні води промислових підприємств, які можуть містити значні кількості марганцю внаслідок технологічних процесів.

Висновки

Дослідження вказують на те, що якісні характеристики річкових вод у басейні Південного Бугу формуються під впливом як природно-геохімічного фону, так і антропогенної трансформації. Генезис хімічного складу поверхневих вод пов'язаний із підземним живленням із тріщин них зон Українського кристалічного щита, а різна мінералізація водоносних горизонтів зумовлює неоднорідність гідрохімічного режиму річок басейну.

Моніторинг водневого показника pH підтвердив його ключову роль у регулюванні розчинності, міграції та токсичності важких металів. Сезонні коливання pH (нормативне значення 6,5–8,5) відображають вплив температури та біологічних процесів: у теплий період року активізація фотосинтезу сприяє підвищенню pH до лужних значень, тоді як у холодний сезон зростання розчинності CO_2 призводить до його зниження.

Дослідження вмісту заліза, міді та марганцю теж показало різну сезонну динаміку. Для заліза характерні значні коливання з перевищенням нормативне значення у весняну повінь та стійкі високі концентрації у зимову межень, що свідчить про наявність стабільних джерел забруднення та ризик повторної мобілізації з донних відкладів. Концентрації міді залишаються відносно стабільними протягом року, що пояснюється її здатністю зв'язуватися з органічною речовиною та мінеральними частинками. Марганець демонструє перевищення нормативне значення у весняний та зимовий періоди, що зумовлено як природними процесами вилуговування руд, так і антропогенними джерелами – стічними водами промислових підприємств.

Таким чином, отримані результати підтверджують, що pH та концентрації важких металів є взаємопов'язаними параметрами, які визначають якість води та екологічну безпеку річкових екосистем. Виявлені закономірності просторово-часового розподілу металів та сезонні зміни кислотно-лужного балансу створюють наукове підґрунтя для розробки природоохоронних заходів, спрямованих на зниження негативного впливу антропогенних факторів, запобігання вторинному забрудненню та забезпечення сталого функціонування басейну Південного Бугу. У цьому контексті доцільним є посилення системи моніторингу, що дозволить своєчасно виявляти критичні зміни у хімічному складі води та оперативно реагувати на них, а також інтеграція отриманих даних у регіональні програми управління водними ресурсами, що сприятиме формуванню збалансованої стратегії охорони довкілля та сталого розвитку території.

Внесок авторів: всі автори зробили рівний внесок у цю роботу
Конфлікт інтересів: автори повідомляють про відсутність конфлікту інтересів
Декларація про використання генеративного штучного інтелекту: Автори використовували інструменти генеративного штучного інтелекту (GenAI) для допоміжної роботи: модель Gemini було використано під час перевірки правильності перекладу з однієї мови на іншу. Усі результати роботи з цими інструментами були ретельно контрольовані, перевірені та, за необхідності, відредаговані авторами. Автори несуть повну відповідальність за зміст та цілісність публікації.

Authors Contribution: All authors have contributed equally to this work
Conflict of Interest: The authors declare no conflict of interest

Declaration of use of generative artificial intelligence: The authors utilized generative artificial intelligence (GenAI) tools in a supportive capacity: the Gemini model was used to check the accuracy of a translation from one language to another. All outputs from these tools were carefully supervised, reviewed, and, where necessary, edited by the authors. The authors retain full responsibility for the content and integrity of the publication.

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Monitoring of heavy metals for assessing water quality in Southern Bug basin

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ABSTRACT

Introduction. The article presents the results of comprehensive studies on the chemical composition of river waters in the Southern Bug River basin (central Ukraine), formed under the influence of combined natural geochemical processes and anthropogenic pressure. As the main water artery of the central region, the river serves as a key source of domestic and drinking water supply and acts as a strategic resource for ensuring the state's energy and food security. Monitoring this system is essential for forecasting changes in water discharge and quality under climate challenges.
The purpose of the article. The aim of the study is to identify spatio-temporal patterns of heavy metal distribution in the waters of the Southern Bug basin and to assess their impact on water quality and the environmental safety of river ecosystems.
Data and methods. A comprehensive approach was applied, including hydrochemical monitoring, analysis of seasonal pH fluctuations, determination of iron, copper, and manganese concentrations, and evaluation of the influence of natural and anthropogenic factors (precipitation, land use, redox potential).
Results. Groundwater, which accumulates degradation products of crystalline rocks of the Ukrainian Shield, was found to be the primary source of river recharge. Spatial heterogeneity of water composition is caused by varying mineralization of aquifers. Zones of the most intense technogenic impact were identified. Seasonal pH fluctuations (6.5–8.76) regulate solubility, migration, and toxicity of heavy metals. Iron concentrations (0.2–0.36 mg/dm³) exceeded regulatory values during spring floods, while copper remained relatively stable (0.0013–0.095 mg/dm³). Manganese concentrations reached 0.12 mg/dm³, exceeding standards due to both natural and anthropogenic factors, including mobilization from sediments under changing redox and temperature regimes. The intensity of metal leaching correlated with precipitation and agricultural land use.
The scientific novelty. For the first time, a correlation between seasonal pH fluctuations and heavy metal concentrations was established for the Southern Bug basin, determining water quality and ecological stability of the river system.
Practical significance. The identified patterns of spatio-temporal metal distribution provide a scientific basis for developing environmental protection measures aimed at reducing anthropogenic impacts, preventing secondary pollution, and ensuring sustainable functioning of the Southern Bug basin. The proposed approaches can be applied to optimize the regional environmental monitoring system for water resources.

ARTICLE INFO

Manuscript received
11 February 2026

Revised manuscript received
17 March 2026

Manuscript accepted
25 May 2026

Available online
30 May 2026

Keywords:

environmental monitoring, river water pollution, pH value, heavy metal pollution, seasonal pollution dynamics, hydro-ecosystems, environmental safety, regulatory value, anthropogenic pressure, river basins.

In cites: Zalizniak Yana, Sonko Sergiy, Vasylenko Olga, Balabak Oleksandr, Balabak Alla, Hurskyi Ihor (2026). Monitoring of heavy metals for assessing water quality in Southern Bug basin. *Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology*, (64), 383–394. https://doi.org/10.26565/2410-7360-2026-64-29 [In Ukrainian]

https://doi.org/10.26565/2410-7360-2026-64-30

UDC 911.52:528.8:004.9

Forest Cover Changes in Marat Longri Patradisa Longnit Forest Complex of Karbi Anglong District, North East India

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ABSTRACT

Purpose. This study analyzes the spatio-temporal dynamics of forest cover in the Marat Longri–Patradisa–Longnit Forest Complex (MLPL), Karbi Anglong district, Assam, over the period 1994–2024. The forest complex is an ecologically significant landscape in Northeast India, supporting rich biodiversity and serving as a critical habitat for several threatened species. The objectives were to quantify changes in major forest types, examine land use and land cover (LULC) transitions, assess anthropogenic drivers of forest degradation, and evaluate their implications for biodiversity conservation, particularly for the Western Hoolock Gibbon (Hoolock hoolock).

Methodology. Multi-temporal satellite imagery, including Landsat 4–5 TM (1994 and 2004) and BHUVAN LISS IV (2014 and 2024), was used for the analysis. All images were radiometrically and geometrically corrected to ensure temporal consistency. The study area was classified into seven LULC categories: Semi-Evergreen Forest, Moist Mixed Deciduous Forest, Scrub Forest, Degraded Forest, Agricultural Land/Shifting Cultivation, Built-up Areas, and Water Bodies. Pixel-based supervised classification and post-classification change detection were performed using ArcGIS 10.3. Classification accuracy was evaluated using Producer Accuracy, User Accuracy, Overall Accuracy, and Kappa statistics.

Results. The results indicate a significant decline in Semi-Evergreen Forest and Moist Mixed Deciduous Forest, accompanied by notable increases in Degraded Forest, Scrub Forest, Agricultural Land/Shifting Cultivation, and Built-up Areas. These changes reflect increasing anthropogenic pressures, including shifting cultivation, illegal and selective logging, agricultural expansion, infrastructure development, and settlement growth. The classified maps achieved high accuracy, with average User Accuracy ranging from 90.64% to 96.53% and Kappa values between 0.81 and 0.93, confirming the reliability of the classification. The observed forest changes have intensified habitat fragmentation, reduced canopy connectivity, and degraded habitat quality for forest-dependent wildlife.

Scientific novelty and practical significance. This study presents a comprehensive long-term assessment of forest cover dynamics in the MLPL Forest Complex and demonstrates the ecological consequences of landscape transformation. By linking forest cover change with biodiversity conservation, particularly the conservation of the Western Hoolock Gibbon, the findings provide a scientific basis for sustainable forest management, restoration of degraded forests, regulation of shifting cultivation, and strengthened community-based conservation initiatives to enhance ecological resilience in Northeast India.

ARTICLE INFO

Manuscript received
30 September 2025

Revised manuscript received
6 November 2025

Manuscript accepted
25 May 2026

Available online
30 May 2026

Keywords:

Forest cover change, Remote sensing, GIS, Hoolock Gibbon, Habitat fragmentation, Karbi Anglong, Northeast India, Land use and land cover (LULC), Biodiversity conservation.

Introduction

Forest cover changes have now emerged as a critical environmental issue at the global level and even in India, with ongoing large-scale changes in forest extent and composition remodeling landscapes and ecosystems [1, 2]. Though land use and forest cover are frequently employed synonymously, they express different meanings in natural resource management and environmental monitoring [3, 4]. Forest cover describes the physical extent and spatial distribution of vegetation, especially tree canopies, on the surface of the Earth, whereas land

In cites: Kashyap Parag Jyoti, Bose Sahana (2026). Forest Cover Changes in Marat Longri Patradisa Longnit Forest Complex of Karbi Anglong District, North East India. *Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology*, (64), 395–404. https://doi.org/10.26565/2410-7360-2026-64-30



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use describes human land use and management activities like agriculture, habitation, and infrastructure development [5, 6]. Forested cover change in India has been driven by rapid population increase, expansion in agriculture, urban expansion, and enhanced demand for natural resources [7, 8]. These anthropogenic forces, combined with infrastructural growth and shifting cultivation patterns, have resulted in extensive deforestation and forest degradation in various regions [9, 10]. The importance of research on forest cover change became apparent during the mid-1970s, and by the mid-1980s scientists realized that forests played a crucial role as sources and sinks of carbon, highlighting their impact on the global carbon cycle and climate balance [11, 12].

Forest cover change is currently identified as one of the most significant drivers of global and regional environmental change [13, 14]. Knowledge of the spatial and temporal patterns of forest cover is thus critical for successful land resource management and conservation planning [15, 16]. The pattern and pace of forest cover change, however, differ considerably among Indian regions [17].

In Northeast India, where forest ecosystems harbor exceptional biodiversity and many indigenous communities, forest cover change has been especially significant [18, 19]. Complex socio-ecological interactions, where traditional shifting cultivation, population pressure, and development activities together determine forest dynamics, are the characteristics of the region. Studies revealed that these changes impact natural resources, agricultural productivity, economic development, and ecological stability directly or indirectly [20, 21].

Therefore, forest cover change analysis is imperative to ensure effective monitoring, evaluation, conservation, and planning [22, 23]. Human activities have drastically changed the forested ecosystems of Northeast India over the decades [24]. As forest cover includes both natural and human-altered vegetation, it is crucial to have a holistic knowledge of its dynamics for effective decision-making, ecosystem restoration, and sustainable forest resource management [25, 26].

The Karbi Anglong district is especially significant for the purpose of forest protection in Assam. It is the most extensive district in the state by surface area and has the highest percentage of forest cover [27, 28]. The district consists of a number of different forest complexes, and among them the Marat Longri–Patradisa–Longnit Forest Complex is particularly significant. This forest complex is rich in flora and fauna and is one of the most under-scientifically unexplored areas in Assam. It is the largest habitat area (around 52%) of the endangered Western Hoolock Gibbon (Hoolock hoolock), and also provides shelter to the maximum population of Asian Elephants in Northeast India [29]. Therefore, analyzing forest cover dynamics in this region is of critical importance.

In this context, the object of the study is the forest cover of the Marat Longri–Patradisa–Longnit Forest Complex. The subject of the study is the spatio-temporal changes in forest cover and land use/land cover patterns from 1994 to 2024. The main purpose of the study is to assess changes in forest cover, identify the major anthropogenic drivers responsible for these changes, and evaluate their implications for biodiversity conservation, with particular emphasis on the canopy-dependent Western Hoolock Gibbon (Hoolock hoolock).

1. Materials and Methods

Study Area

The Marat Longri–Patradisa–Longnit Forest Complex is situated in the Karbi Anglong district of Assam (Figure 1). It lies between the geographical coordinates of 93°08′E to 93°30′E longitude and 25°45′N to 26°10′N latitude, covering a total area of approximately 802 sq. km. The complex comprises seven major Reserve Forests (R.F.) and District Council Reserve Forests (D.C.R.F.), namely Meyungdisa (D.C.R.F.), Disama (R.F.), Kaki (R.F.), Englongkiri (D.C.R.F.), Patradisa (R.F.), Longnit (R.F.), and Khonbamon (D.C.R.F).

Data Source

The study employed multi-temporal satellite datasets, including Landsat 4–5 TM C2 L2 imagery from 1994 and 2004, and BHUVAN LISS IV imagery from 2014 and 2024, sourced from the USGS Earth Explorer and NRSC BHUVAN platforms, respectively. The Landsat images had a spatial resolution of 30 m, while the LISS IV data offered a finer resolution of 5.8 m. All datasets were acquired in TIFF format and processed using ArcGIS 10.3. Before analysis, radiometric and geometric corrections were applied to reduce sensor-related noise, atmospheric distortions, and spatial inaccuracies, thereby ensuring spatial precision and spectral consistency across all time periods.

To maintain uniformity among datasets and ensure reliable temporal comparisons, image resampling was conducted to reconcile differences in spatial resolution. Seven categories were delineated: Semi-Evergreen Forest, Mixed Moist Deciduous Forest, Scrub Forest, Degraded Forest, Agricultural Land/Shifting Cultivation, Built-up Areas, and Water Bodies. All images were geo-referenced to the WGS 84 coordinate system using the UTM Zone 46N projection. False Color Composite (FCC) images were generated to aid in visual interpretation. The study boundary of the Marat Longri–Patradisa–Longnit Forest

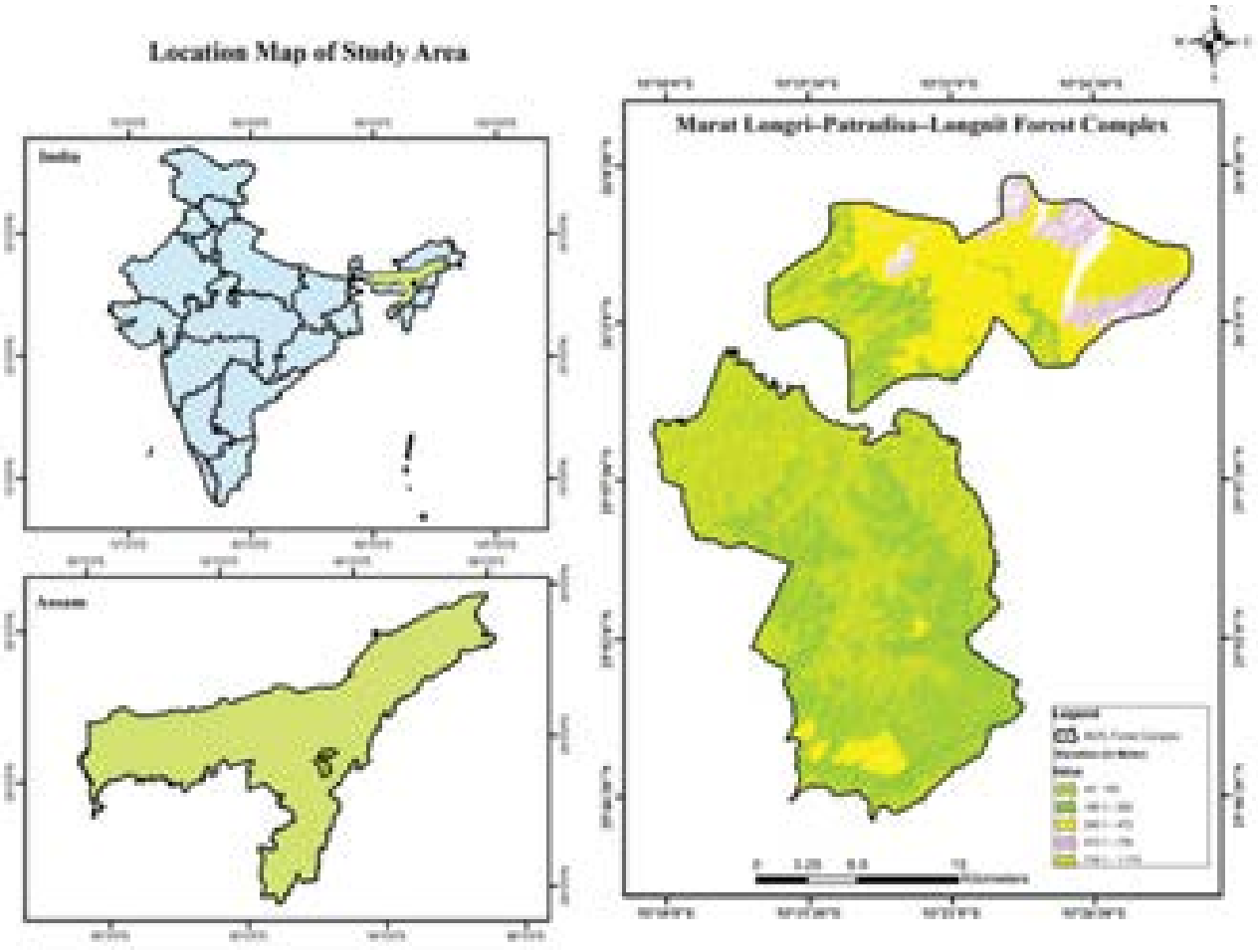


Fig. 1. Location map of Study Area

Complex was defined using Survey of India Toposheets (Nos. 83G/1, 83G/5, 83F/4, and 83F/8; scale 1:50,000). Finally, pixel-based supervised classification techniques were employed to generate forest cover maps for each time period.

Satellite data information:

A post-classification change detection approach was applied using a change matrix to assess and quantify temporal variations in forest cover. The matrix depicts the transitions among different forest cover categories across the study period from 1994 to 2024. The magnitude of change for each forest cover class was computed using the following equation:

$$ti = t_1 - t_2 \quad (1)$$

Where, ti signifies the degree of change in classes i, t_1 denotes the base image, and t_2 denotes the most recent image.

The following formula was used to calculate the percentage change for each forest cover category:

$$Pci=(t_1-t_2)/t_2\times100 \quad (2)$$

Where, t_2 represents the most recent image, t_2 represents the base image and Pci represents the percentage of change in class i [30].

Accuracy assessment is a vital component of image classification, ensuring the dependable detection, interpretation, and evaluation of changes [31]. To accomplish this, the classified results were validated using the original mosaic, Google Earth imagery, and GPS-based reference points. A confusion matrix was generated by superimposing the classified forest cover map onto ground truth data to evaluate its accuracy. Various statistical measures such as overall accuracy, Kappa coefficient, producer's accuracy, and user's accuracy were calculated [30]. The computation of these accuracy indices followed

Table 1

Satellite Data information

Sensor	Resolution (in m.)	Path/Row/orbit/Scene Number	Data format	Acquisition time	Purpose
LANDSAT 4-5	30	136/42	Geotiff	27/11/1994	Forest Cover Analysis
LANDSAT 4-5	30	136/42	Geotiff	08/02/2004	Forest Cover Analysis
LISS 4	5.8	014649011200053	Geotiff	14/02/2014	Forest Cover Analysis
LISS 4	5.8	036801011200053	Geotiff	10/01/2024	Forest Cover Analysis

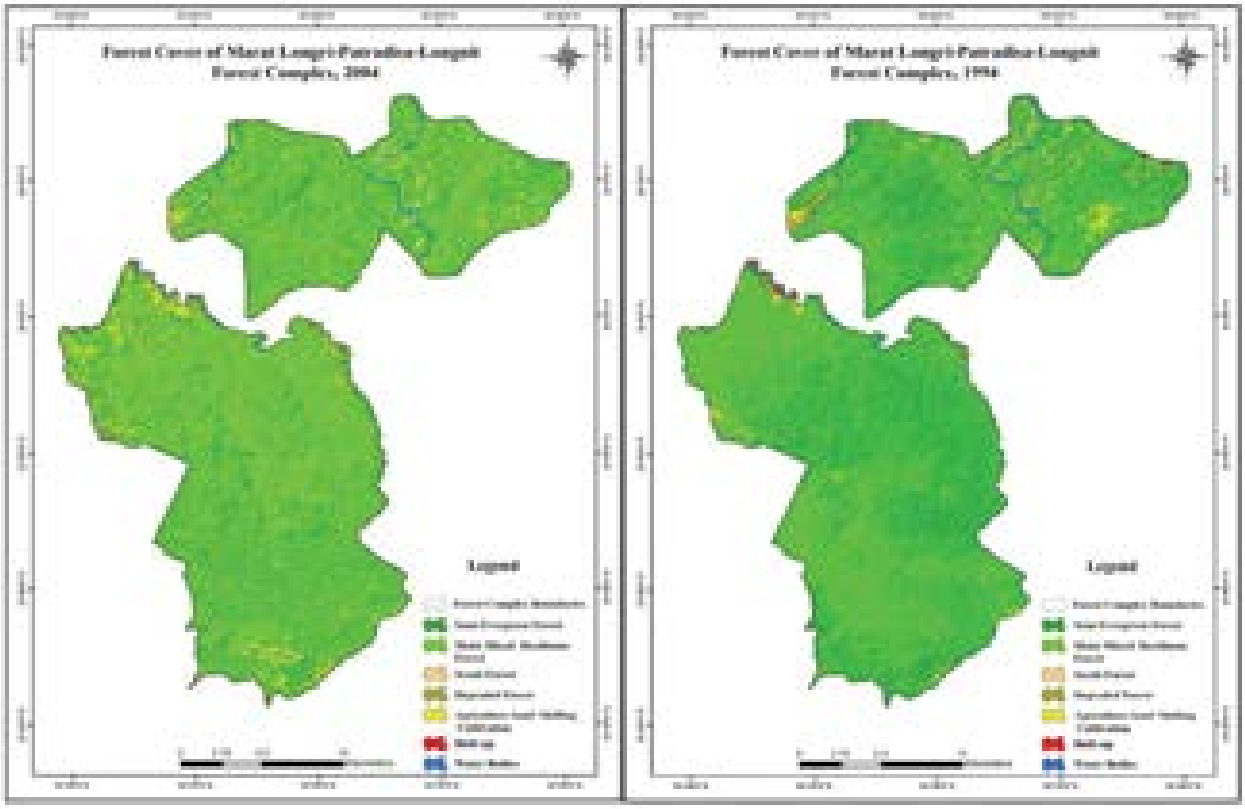


Fig. 2. Forest Cover of MLPL Forest Complex 1994 and 2004

the methodologies described by Islami et al. (2022) and Garg et al. (2016) [32, 33].

Producer accuracy:

$$\frac{\text{Number of Correctly Classified Pixels in each Category}}{\text{Total Number of Reference Pixels in that Category (The Column Total)}} \times 100 \quad (3)$$

User Accuracy:

$$\frac{\text{Number of Correctly Classified Pixels in each Category}}{\text{Total Number of Reference Pixels in that Category (The Row Total)}} \times 100 \quad (4)$$

Overall Accuracy:

$$\frac{\text{Total number of correctly classified pixels}}{\text{Total number of pixels in the matrix table}} \times 100 \quad (5)$$

Kappa Coefficient:

$$\frac{N \sum_{i}^{r=1} x_{ii} - \sum_{i}^{r=1} (x_{i+} * x+i)}{N^2 - \sum_{i}^{r=1} (x_{i} + * x+i)} \quad (6)$$

Where, r is the matrix's number of rows, xii denotes the total number of pixels in row i and column i that were correctly classified, and xi+ and x + i denote the marginal sums of row i and column i.

Result and Analysis

The temporal assessment of forest cover and land use changes in the Marat Longri–Patradisa–Longnit Forest Complex from 1994 to 2024 reveals substantial alterations across various land cover classes (Table 2). The results indicate a consistent decline in dense forest categories, accompanied by a marked expansion of degraded, scrub, and human-modified areas over the three decades (Figure 2 and 3).

The Semi-Evergreen Forest category declined markedly from 285.03 sq. km in 1994 to 158.40 sq. km in 2024, representing a net loss of 126.63 sq. km. This substantial reduction indicates large-scale deforestation and canopy thinning, primarily driven by shifting cultivation, logging, and other anthropogenic pressures. Similarly, the Moist Mixed Deciduous Forest cover decreased from 297.90 sq. km to 248.26 sq. km over the same period, suggesting ongoing degradation and conversion of late-successional forest stands into secondary or disturbed forest types. In contrast, both Scrub Forest and Degraded Forest classes exhibited significant expansion. The scrub forest area increased from 82.09 sq. km in 1994 to 120.44 sq. km in 2024, while degraded forest expanded from 41.20 sq. km to 122.31 sq. km. These increases reflect continued ecological deterioration and the replacement of dense canopy forests with fragmented, low-quality vegetation indicating a shift toward secondary succession stages.

The Agriculture and Shifting Cultivation area grew moderately, from 32.52 sq. km in 1994 to 46.10 sq. km in 2024, emphasize the persistent dependence of local communities on forest resources for subsistence agriculture. Likewise, the Built-up area expanded sharply from 27.87 sq. km to 71.10 sq. km, reflecting increased settlement growth, infrastructure development,

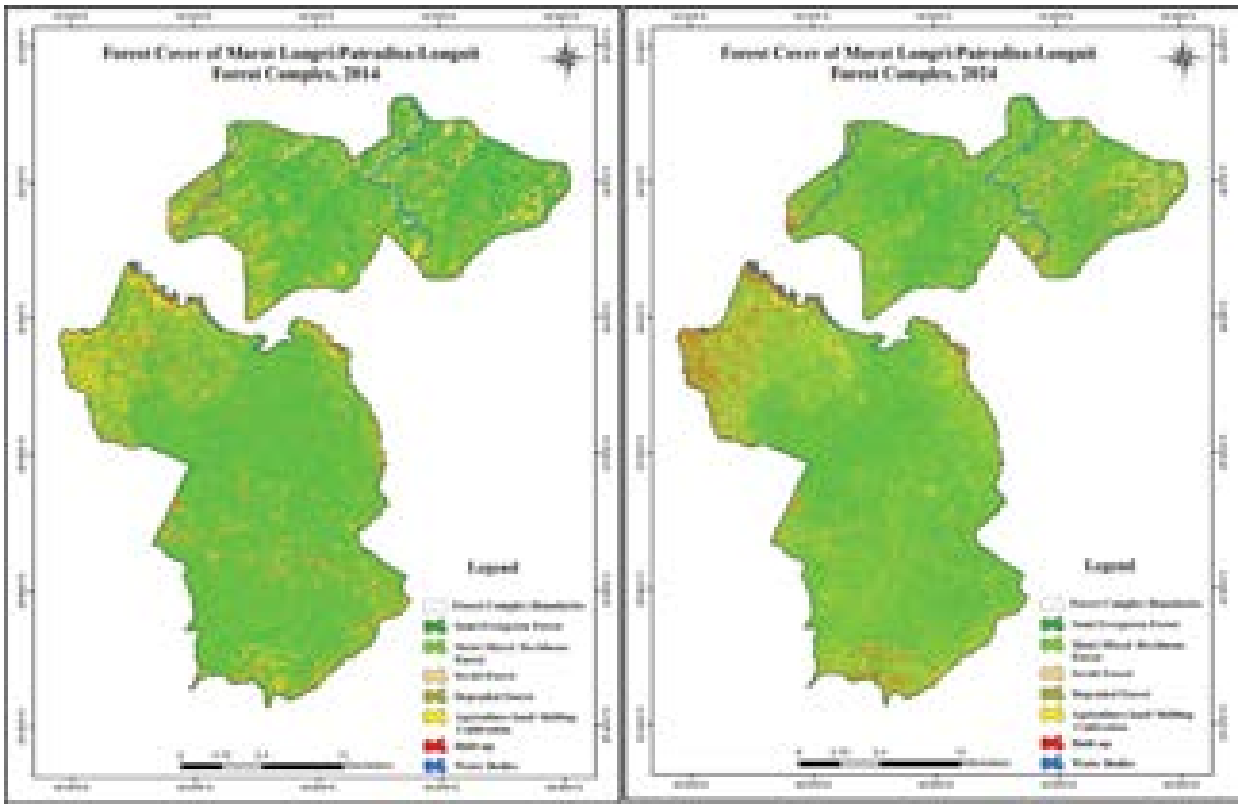


Fig. 3. Forest Cover of MLPL Forest Complex 2014 and 2024

and human encroachment into forested regions. In contrast, the Water Bodies category remained relatively stable throughout the study period, maintaining an average area of approximately 34.8 sq. km, which suggests minimal hydrological change within the complex.

The analysis reveals a consistent pattern of forest loss and landscape transformation across the study period. The combined area of dense forests (Semi-Evergreen and Moist Deciduous) declined from 582.93 sq. km in 1994 to 406.66 sq. km in 2024, indicating a net loss of 176.27 sq. km of forest cover. While this decline highlights an intensifying trend of deforestation, the concurrent expansion of degraded forest, scrubland, and built-up areas emphasize growing anthropogenic stress on the ecosystem. These transformations carry significant ecological consequences, particularly for canopy-dependent species such as the Western Hoolock Gibbon (Hoolock hoolock), which rely on contiguous forest cover for their survival and movement.

2. Discussion

The spatiotemporal analysis of land use and forest cover changes in the Marat Longri–Patradisa–Longnit Forest Complex for the period 1994–2024 presents a clear trend of ecological transformation characterized by increasing deforestation and habitat fragmentation. The quantitative trends summarized in Table 3 and Figure 4 clearly show a steady reduction in dense forest classes especially

Table 2

Area of different classified forest cover classes in the Marat Longri–Patradisa–Longnit Forest Complex

Classes	1994 (Area in km²)	2004 (Area in km²)	2014 (Area in km²)	2024 (Area in km²)
Semi Evergreen Forest	285.03	243.05	176.58	158.4
Moist Mixed Deciduous	297.9	295.66	268.1	248.26
Scrub Forest	82.09	93.39	103.92	120.44
Degraded Forest	41.2	66.39	108.27	122.31
Agriculture land/ Shifting Cultivation	32.52	38.29	45.92	46.1
Built-up	27.87	29.89	63.83	71.1
Water Bodies	34.81	34.75	34.8	34.81
Total	801.42	801.42	801.42	801.42

Table 3

Forest Cover changes of MLPL Forest Complex 1994-2024

Forest Cover Class	1994 Area in (%)	2004 Area in (%)	2014 Area in (%)	2024 Area in (%)	Change (1994–2004)	Change (2004–2014)	Change (2014–2024)
Semi-Evergreen Forest	35.57	30.33	22.03	19.76	–5.24	–8.29	–2.27
Moist Mixed Deciduous	37.17	36.89	33.45	30.98	–0.28	–3.44	–2.48
Scrub Forest	10.24	11.65	12.97	15.03	+1.41	+1.31	+2.06
Degraded Forest	5.14	8.28	13.51	15.26	+3.14	+5.23	+1.75
Agriculture/Shifting Cultivation	4.06	4.78	5.73	5.75	+0.72	+0.95	+0.02
Built-up	3.48	3.73	7.96	8.87	+0.25	+4.23	+0.91
Water Bodies	4.34	4.34	4.34	4.34	–0.01	+0.01	+0.00

Semi-Evergreen Forests and Moist Mixed Deciduous Forests paired with the continuous increase of degraded and scrubland categories.

The Semi-Evergreen Forest category underwent the sharpest loss, decreasing from 35.56% in 1994 to 19.76% in 2024. The 15.80% loss accounts for widespread canopy loss and deforestation due to anthropogenic factors of shifting cultivation, logging, and land clearing for settlement and agriculture. As with Moist Mixed Deciduous Forests, which decreased from 37.17% to 30.98%, this indicates continued conversion of mature forest stands into secondary growth or disturbed terrain. The steepest fall in both forest categories was between 2004 and 2014, which is a time most likely to be marked by increased human activity and uncontrolled land conversion. On the other hand, Scrub Forest and Degraded Forest classes experienced a sharp rise during the study period. Scrub Forests grew from 10.24% in 1994 to 15.03% in 2024, whereas Degraded Forests grew from 5.14% to 15.26%. These trends indicate that previously dense forests are experiencing successional regression, whereby canopy loss and soil loss have resulted in dense cover of poor-quality vegetation. This trend is consistent with other research in tropical and sub-tropical forest habitats of Northeast India [34, 35], where such processes of degradation have been attributed to expanding human habitation and resource use. The Built-up and Agriculture/Shifting Cultivation categories also expanded, reflecting increasing human encroachment and reliance on forest products for survival. The Built-up category more than doubled from 3.48% to 8.87% representing accelerated settlement growth and infrastructure development. Agricultural and shifting cultivation areas grew comparatively modestly, indicating ongoing livelihood dependency on land use. These patterns altogether hint at growing anthropogenic alteration of the environment, sometimes at the cost of ecological health. Conversely, Water Bodies class showed minimal variation, with a mean of 4.3% of the total area over the study period. This stability indicates that hydrological conditions have not been significantly affected by the changing land use in the surrounding areas, although localized effects on water quality and flow regimes cannot be eliminated.

3. Accuracy Assessment

Accuracy testing of the forest cover classification for the period 1994-2024 shows good reliability

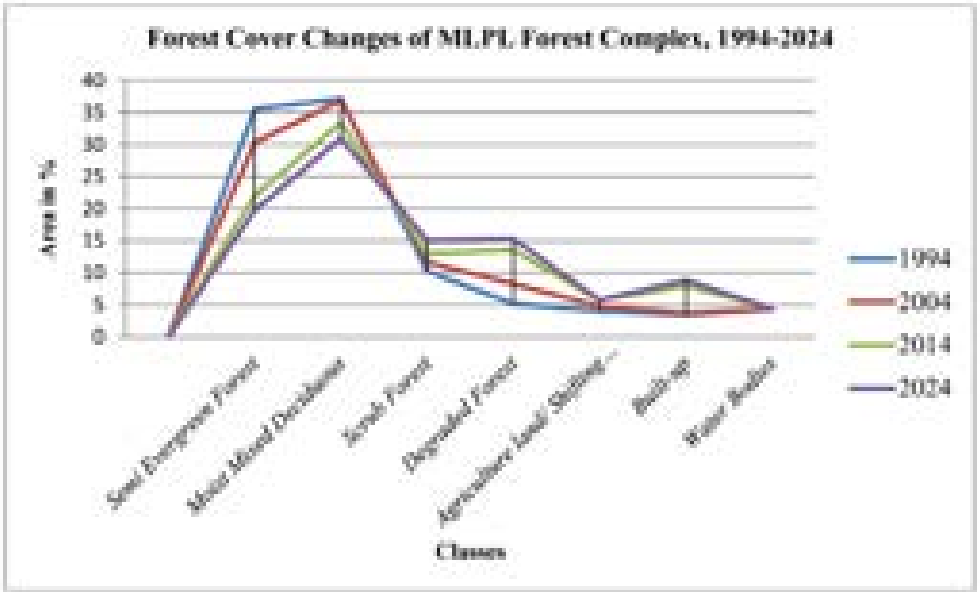


Fig. 4. Forest Cover changes of MLPL Forest Complex 1994-2024

Table 4

Accuracy assessment of forest cover classification in the Marat Longri–Patradisa–Longnit Forest Complex from 1994 to 2024, showing Producer Accuracy, User Accuracy, average User Accuracy, and estimated Kappa statistics for each year

Classes	1994 Producer Accuracy	1994 User Accuracy	2004 Producer Accuracy	2004 User Accuracy	2014 Producer Accuracy	2014 User Accuracy	2024 Producer Accuracy	2024 User Accuracy
Semi Evergreen Forest	92.11%	96.86%	94.97%	98.85%	98.64%	96.18%	94.72%	85.93%
Moist Mixed Deciduous Forest	96.35%	97.85%	93.12%	98.37%	92.44%	97.89%	92.60%	98.88%
Scrub Forest	94.25%	82.55%	97.89%	95.97%	96.67%	98.72%	90.97%	94.89%
Degraded Forest	99.12%	91.23%	98.45%	98.94%	99.78%	88.49%	99.77%	68.73%
Agricultural land/ Shifting Cultivation	98.97%	99.87%	92.88%	93.88%	99.73%	98.87%	97.72%	97.31%
Built-up	98.44%	87.55%	99.87%	98.72%	90.55%	82.72%	69.95%	89.78%
Water Bodies	78.45%	99.52%	97.82%	90.99%	92.75%	94.65%	75.89%	97.97%
Overall Accuracy	93.91		96.53		93.36		90.64	
Kappa statistics	0.88		0.93		0.87		0.81	

of the results (Table 4). Overall user accuracy varied from 90.64% (2024) to 96.53% (2004), with high consistency between the classified maps and reference data. The related Kappa statistics that take into account agreement by chance ranged from 0.81 to 0.93, corroborating further the quality of the classifications. Small decreases in user accuracy as well as Kappa in 2014 and 2024 indicate enhanced spectral confusion among classes, which is primarily due to anthropogenic land use changes as well as heterogeneity of the landscape. Collectively, these measures confirm the trustworthiness of the satellite-based forest cover maps for the four decades.

4. Conclusion

The spatio-temporal evaluation of the changes in the forest cover during the period of 1994-2024 within the Marat Longri–Patradisa–Longnit Forest Complex shows significant ecological changes driven mainly by human activities. The result reflects a significant reduction in Dense forest categories—particularly Semi-Evergreen and Moist Mixed Deciduous Forests—coupled with a significant increase in Degraded Forests, Scrub Forests, and Built-up lands. These together represent an increasing deforestation pattern, habitat degradation, and fragmentation of the landscape.

The consistent rise in degraded and human-modified land categories indicates more rigorous shifting cultivation, timber removal, agricultural encroachment, and settlement expansion, all of which have greatly altered the natural structure and composition of the vegetation. Even though the area of Water Bodies has exhibited negligible fluctuation, the mass-scale conversion of dense forests to degraded areas is a major threat to the ecological integrity and diversity of the region.

These changes in landscape have serious implications for canopy-associated species like the Western Hoolock Gibbon (Hoolock hoolock), which relies on unbroken forest cover for its existence, mobility, and reproduction. Habitat loss trend highlights the imperative of adopting sustainable forest management, participatory conservation initiatives, and policy initiatives that align local livelihoods with ecological conservation.

In short, the study highlights a relentless pattern of forest decline that, if not addressed, would lead to irreparable ecological harm. Immediate measures addressing reforestation, connectivity of habitats, and peoples' awareness are crucial for saving the existing forests and improving the long-term ecological resilience of the Marat Longri–Patradisa–Longnit Forest Complex.

Внесок авторів: всі автори зробили рівний внесок у цю роботу
Конфлікт інтересів: автори повідомляють про відсутність конфлікту інтересів
Декларація про використання генеративного штучного інтелекту: Автори не використовували інструменти генеративного штучного інтелекту (GenAI) при написанні статті. Автори несуть повну відповідальність за зміст та цілісність публікації.

Author Contributions: All authors have contributed equally to this work
Competing interests: The authors declare no competing interests
Declaration of use of generative artificial intelligence: The authors did not use generative artificial intelligence (GenAI) tools when writing the article. The authors retain full responsibility for the content and integrity of the publication.

Подяка. Автори висловлюють подяку Спеціальному головному охоронцю лісів (Spl. PCCF), Карбі Англонг, Ассам, і Автономній раді Карбі Англонга за надання дозволу на проведення досліджень в охоронюваних територіях. Ми висловлюємо щиру подяку кафедрі географії Ассамського університету за їхню постійну підтримку під час навчання. Автори також хочуть висловити свою щиру вдячність доктору Пранджіту Кумару Сарма, доценту кафедри географії коледжу Мангалдай, за його щедре керівництво та підтримку.

Acknowledgement. The authors gratefully acknowledge the Special Principal Chief Conservator of Forest (Spl. PCCF), Karbi Anglong, Assam, and the Karbi Anglong Autonomous Council for granting permission to conduct research in the protected areas. We extend our sincere thanks to the Department of Geography, Assam University, for their continuous support during the study. The authors also wish to express their heartfelt appreciation to Dr. Pranjit Kumar Sarma, Associate Professor, Department of Geography, Mangaldai College, for his generous guidance and support.

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Зміни лісового покриву в лісовому комплексі Марат Лонгрі Патрадіса Лонгніт округу Карбі Англонг, Північно-Східна Індія

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АНОТАЦІЯ

Метою дослідження є аналіз просторово-часової динаміки лісового покриву в лісовому комплексі Марат Лонгрі–Патрадіса–Лонгніт (MLPL) в окрузі Карбі Англонг (Ассам, Індія) протягом 1994–2024 рр. Комплекс є важливим осередком біорізноманіття Північно-Східної Індії та середовищем існування багатьох рідкісних видів. Дослідження спрямоване на оцінку змін основних типів лісів, трансформації землекористування, впливу антропогенних чинників на деградацію лісів та наслідків цих процесів для збереження біорізноманіття, зокрема західного Хулоцького гібона. Використано супутникові знімки Landsat 4–5 TM за 1994 і 2004 рр. та BHUVAN LISS IV за 2014 і 2024 рр. Після попередньої обробки територію класифіковано за сімома категоріями землекористування та земного покриву: напіввічнозелені, вологі змішані листяні, чагарникові та деградовані ліси, сільськогосподарські угіддя, забудовані території й водойми. Для аналізу застосовано контрольовану піксельну класифікацію та післякласифікаційне виявлення змін у ArcGIS 10.3. Достовірність результатів оцінено за показниками точності виробника, користувача, загальної точності та статистикою Каппа. Результати засвідчили суттєве скорочення площ напіввічнозелених і вологих змішаних листяних лісів та одночасне збільшення площ деградованих і чагарникових лісів, сільськогосподарських угідь і забудованих територій. Це свідчить про посилення антропогенного впливу, пов'язаного з вирубуванням лісів, розвитком сільського господарства, інфраструктури та поселень. Класифікація характеризувалася високою точністю: середня точність користувача становила 90,64–96,53 %, а статистика Каппа – 0,81–0,93. Виявлені зміни призвели до фрагментації середовищ існування та погіршення умов для видів, залежних від лісових екосистем. Дослідження є комплексною довгостроковою оцінкою динаміки лісового покриву MLPL і демонструє необхідність сталого управління лісами, відновлення деградованих ділянок, регулювання змінного землеробства та посилення природоохоронних заходів для збереження біорізноманіття й підвищення екологічної стійкості регіону.

ІНФОРМАЦІЯ ПРО СТАТТЮ :

Manuscript received
16 October 2025

Revised manuscript received
16 December 2025

Manuscript accepted
25 May 2026

Available online
30 May 2026

Ключові слова:

зміна лісового покриву, дистанційне зондування, ГІС, Хулоцький гібон, фрагментація середовища існування, Карбі Англонг, Північно-Східна Індія.

https://doi.org/10.26565/2410-7360-2026-64-31

UDC: 630.561.24:630.43:630.174.754

Impact of surface fire on the radial growth of Scots pine in Polissya landscapes

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ABSTRACT

Introduction. Forest fires are one of the key destabilizing factors affecting the functioning of forest ecosystems, influencing their productivity, biodiversity, and ecosystem services. Under the conditions of climate change and increasing anthropogenic pressure, particularly due to military actions in Ukraine, the frequency and intensity of fires are rising, which necessitates the study of post-fire processes in the forests of **Polissya.**
The aim of the research is to determine the patterns of surface fire impact on the radial growth of Scots pine in middle-aged pine stands of **Polissya.**
Methods. The study is based on a combination of dendrochronological analysis, forest inventory methods, and statistical data processing. Cores were collected from the fire-damaged stand and from a control (undamaged) stand. Local tree-ring chronologies were developed, and indexing using moving-average smoothing was applied. The dynamics of latewood, earlywood, and annual rings were compared between the fire-damaged plot and the control plot for the period 2020–2024. Correlation and regression analyses between growth indices and char height on the stem were performed.
Results. A significant reduction in radial growth was found in the year of the fire and in the following period, with a maximum depression in 2023, which was exacerbated by dry climatic conditions. Latewood turned out to be the most sensitive indicator of fire impact, as its width in the damaged stand was significantly smaller compared to the control. Growth recovery for trees that remained viable occurred within two years. A statistically significant relationship was found between latewood indices and char height. Although the char height on the damaged stand varied within the range of 175–250 mm, i.e., the damage can be classified as moderate to severe, the radial growth recovery of the trees that remained alive occurred within two years. This is because the depth of bark charring was shallow, and the middle-aged pine stands have thick bark that protected the cambium, phloem, and conductive tissues of the wood from fire damage. Moreover,

ARTICLE INFO

Manuscript received 1
1 February 2026

Revised manuscript received
17 March 2026

Manuscript accepted
25 May 2026

Available online
30 May 2026

In cites: Koval Iryna, Maksymenko Nadiya, Martynchuk Ivan, Andreieva Olena, Matkovska Svitlana, Lashchenko Andriy (2026). Impact of surface fire on the radial growth of Scots pine in Polissya landscapes. *Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology*, (64), 405–414. https://doi.org/10.26565/2410-7360-2026-64-31



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as a result of sanitary felling after the fire, 14% of the trees were lost, which improved light conditions and nutrient availability for the remaining trees. The differences between earlywood and annual ring widths in the damaged stand and the control were insignificant during the pre-fire period, the year of the fire, and the post-fire period. The largest - was found for 2023, when the difference was 22%.

Analysis of the latewood/earlywood ratio showed a decrease in this index for the damaged plot in the year of the fire (2022) and the first post-fire year (2023), indicating that this index is suitable for characterizing the impact of stress factors (fires, drought years, etc.) on the radial growth of Scots pine trees.

Conclusions. The impact of the 2022 fire on middle-aged Scots pine stands under thermal stress conditions (temperature deviation of +13–28%) was studied. It was found that latewood is the most sensitive indicator of pyrogenic impact: in the year of the fire, its width decreased by 56% (to 0.20±0.04 mm), while earlywood parameters remained stable. A statistically significant regression relationship between latewood indices and char height was revealed. It is proved that if the cambium remains alive, trees restore their radial growth within two years, indicating their resistance.

Keywords:

radial growth, Pinus sylvestris L., surface fire, dendrochronology, latewood, post-fire dynamics, Polissya, landscape, forest, climate change, sanitary condition of trees, bioindication.

Introduction

Forest fires are among the most powerful factors transforming forest ecosystems, affecting their structure, functioning, and productivity. They cause significant ecological and economic losses, disrupt biogeochemical cycles, and increase greenhouse gas emissions, thereby contributing to global warming [1–3].

In the context of Ukraine, the problem of fires has gained particular urgency due to military aggression, which is accompanied by the large-scale use of incendiary weapons and the "scorched earth" tactic. According to current estimates, a significant proportion of forest ecosystems have been damaged or destroyed, which necessitates research into their post-fire recovery [4-6].

The forests of Polissya attract special attention, where the combination of sandy soils, increased flammability, and climate change (rising temperatures and precipitation deficits) creates preconditions for frequent fires. Despite a considerable number of studies, the issue of radial growth dynamics as an integral indicator of tree vitality after fire remains insufficiently addressed, especially for the conditions of Ukraine.

The aim of the research is to determine the patterns of surface fire impact on the radial growth of Scots pine in middle-aged pine stands of Polissya**.**

The object of the research is a middle-aged pure pine stand damaged by a surface fire in April 2022 and an undamaged stand.

The subject of the research is the response of the radial growth of Scots pine to the impact of a surface fire.

Analysis of recent research and publications. Tree radial growth is an integral indicator of their physiological state, which makes it possible to use it for bioindication of forest stands [7]. Tree recovery after fire is determined both by direct thermal damage and by climatic factors, primarily high temperatures and moisture deficit. In particular, studies of *Pinus pinaster* Aiton in Vesuvius National Park (southern Italy) have shown that in fire-damaged trees with significant crown deformation, suppression of cambial activity, reduced xylem production, delayed phenological phases, and decreased wood plasticity are observed compared to trees undamaged by fire. The authors concluded that substantial limitations of photosynthesis caused by crown defoliation combined with recurrent droughts lead to a sharp decline in radial growth and prevent the return of productivity to the level preceding the fire damage [8].

The general mechanism of tree damage by fires includes three main components: crown damage – high temperatures destroy buds and leaves (scorching) due to convective and radiant heating or direct contact with flames; stem damage – the heat flux penetrates through the bark, causing necrosis of the cambium and phloem, with bark thickness and charring depth serving as critical indicators; root damage – smouldering combustion of litter and organic debris near the tree base can destroy root systems [9].

Studying radial growth in fire-damaged stands allows for informed planning of forest management measures and specification of the required duration of monitoring of pine stands after pyrogenic impact. Modern dendroecological studies indicate that post-fire radial growth dynamics is a complex multifactorial process that depends on fire intensity, climatic conditions, competition levels, and biological species traits [10].

Materials and methods. The methods of comparative ecology, forest inventory, and dendrochronological methods were used [11, 12].

A surface fire occurred in a pine (*Pinus sylvestris* L.*)* stand of the "Korostyshiv Forestry" branch of the state enterprise "Forests of Ukraine" in April 2022. This is a pure, middle-aged pine stand growing in fresh mesic forest site conditions (fresh oak forest type). Cores were collected from the fire-damaged plot and from a control plot (Fig. 1).

The stand grows in fresh mesic forest site conditions. The fire occurred in April 2022. Fifteen cores from the fire-damaged plot and fifteen cores from the control plot were collected in September 2024.

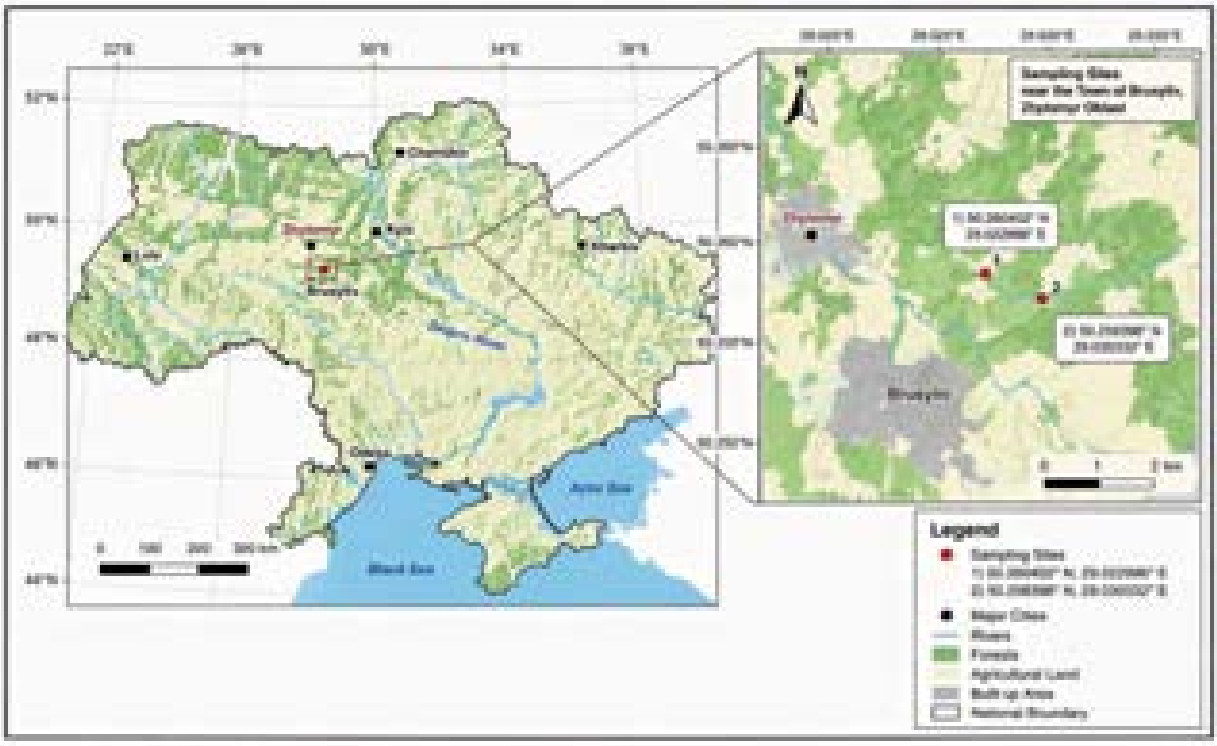


Fig. 1. Map of Ukraine showing the sampling sites.
Note: 1 – fire-damaged pine stand, 2 – control stand

During core collection, the diameter and height of each tree were also measured, and the sanitary condition category was determined. Six categories are distinguished: Category 1 – healthy trees (no signs of weakening): trees with a dense crown, normal growth, no damage to the stem or roots. Category 2 – weakened: crown of medium density, green needles, but reduced growth; minor mechanical damage may be present. Category 3 – severely weakened: open (sparse) crown, needles shortened or pale, presence of top dieback or isolated dead branches. Category 4 – dying trees: crown yellow or brown, needles shedding, more than 2/3 of the crown consists of dead branches, bark begins to peel off. Category 5 – fresh deadwood: trees that died in the current year. Needles dry (red or grey) or already fallen, bark may be infested with stem pests [13].

Cores were taken with a Pressler increment borer at a height of 1.3 m. They were then air-dried, and the widths of earlywood, latewood, and annual ring were measured using a HENSON measuring system with an accuracy of 0.01 mm. Local tree-ring chronologies were obtained for the fire-damaged and control plots.

The dynamics of latewood, earlywood, and annual ring layers were compared between the fire-damaged plot and the control plot over the period 2020–2024 (two years before the fire, the year of the fire (2022), and after the fire).

To remove the age trend and obtain indexed tree-ring chronologies, the 3-year moving average method was used [11].

Statistical data processing, correlation and regression analyses were performed to establish relationships between the indices of tree radial growth and the char height on the stems, as well as the categories of tree sanitary condition.

For the analysis, data from the Zhytomyr weather station (50°16′50″N, 28°39′32″E) were used. Precipitation and temperature normals were calculated for the period 1974–2004. Precipitation normals are a climatological method based on averaging data over a long-term period (usually 30 years or more) for a specific location. This helps to understand whether the current month or year is dry/wet or warm/cold [14].

Results

In order to establish the climatic normals of precipitation and temperature, the corresponding values were averaged over the period 1974–2024. It was found that in the year of the fire (2022), average temperatures were 13% above the normal, while precipitation was 7% below the normal. In 2023, these values were 21% and 33%, respectively; in 2024– 8% and 11%. Consequently, the most extreme year for tree radial growth was 2023 – the year following the fire (Fig. 2).

The unfavourable weather conditions for tree growth in 2023 likely exacerbated the depression of radial growth in the fire-damaged plot.

As of 2024 (the second year after the fire), the sanitary condition of trees in the pine stands on the damaged plot had deteriorated compared to

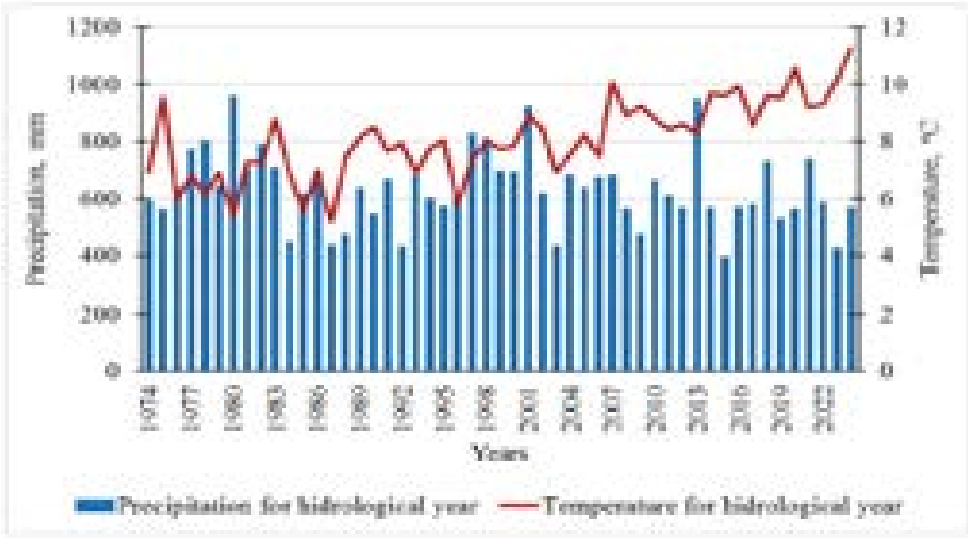


Fig. 2. Dynamics of temperatures and precipitation by hydrological years according to the data from the Zhytomyr weather station

the control. No completely healthy trees were found here (Fig. 3).

Scots pine trees of different sanitary condition categories responded differently on the fire-damaged plot. Weakened trees (category 2) quickly responded to the thinning of the stand caused by the fire, which was manifested in a growth surge in 2023, i.e., in the second year after the fire. Severely weakened or dying trees (categories 3 and 4) showed no significant response to the increased growing space and improved light conditions after the dieback of 14 % of the trees on the damaged plot (Fig. 4).

As noted above, the dynamics of latewood, earlywood, and annual ring layers were compared between the fire-damaged plot and the control plot for the period 2020–2024, i.e., for two years before the fire, the year of the fire (2022), and after the fire (Fig. 5).

In the year of the fire, 2022, the average latewood width on the fire-damaged plot was 0.20±0.04 mm, while on the control plot it was 0.45±0.08 mm, i.e., the difference was 56% and was significant (t_{fact}=2.7, $t_{theor.}$= 2.1 at the 0.05 significance level). In the following year, this difference between the respective wood layers also proved significant at the 0.05 level (t_{fact}=2.7, $t_{theor.}$= 2.1 at the 0.05 significance level), i.e., the latewood width in the damaged stand was 0.29±0.06 mm, while on the control it was 0.58±0.09 mm, meaning it decreased twofold compared to the control. In 2024, the difference between latewood layers in the damaged stand and the control became insignificant. Thus, latewood recovered for the trees that remained alive by the second year after the fire (see Fig. 5 A).

The differences between earlywood and annual ring widths in the damaged stand and the control were insignificant during the pre-fire period, the year of the fire, and the post-fire period. The largest difference in annual radial growth between the damaged and control sample plots was found for 2023, when the difference was 22% (see Fig. 5 B, C).

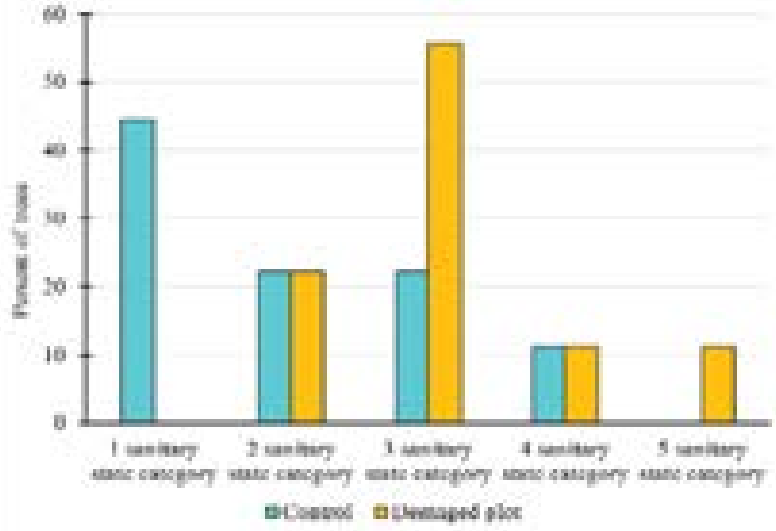


Fig. 3. Sanitary condition of trees on the sample plot damaged by a spring surface fire in 2022 and on the control plot for 2024.

The latewood layers of the trees that remained alive proved to be the most sensitive to fire impact.

Although the char height on the damaged stand varied within the range of 175–250 mm, i.e., the damage can be classified as moderate to severe, the radial growth recovery of the trees that remained alive occurred within two years. This is because the depth of bark charring was

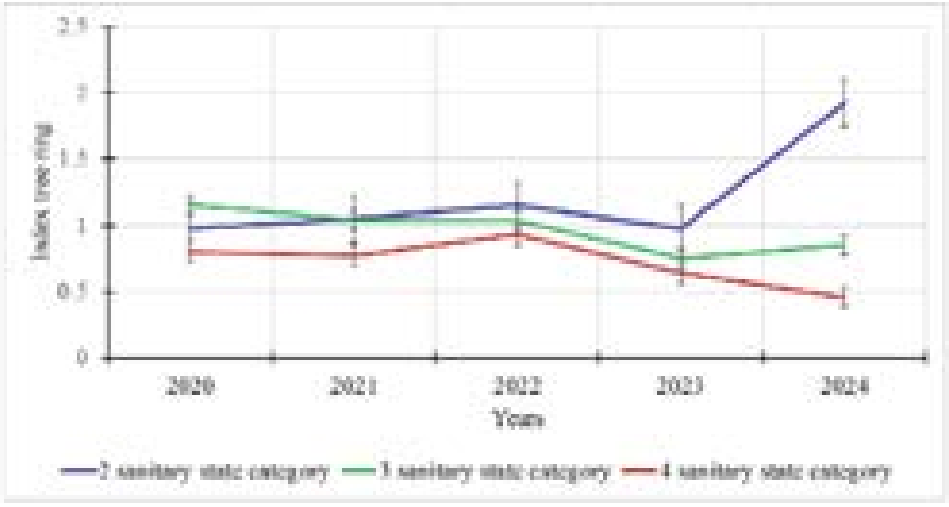
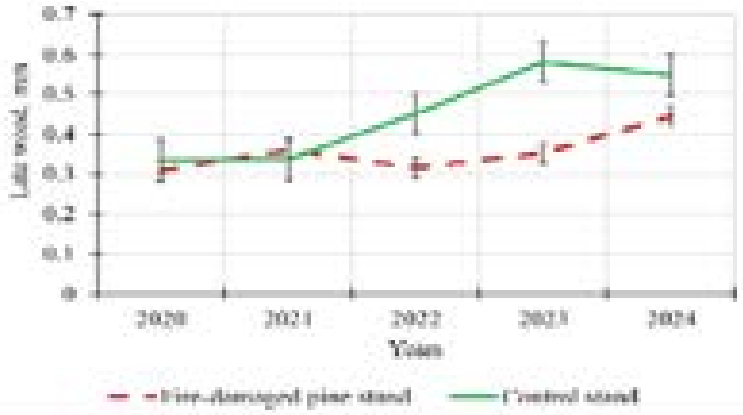
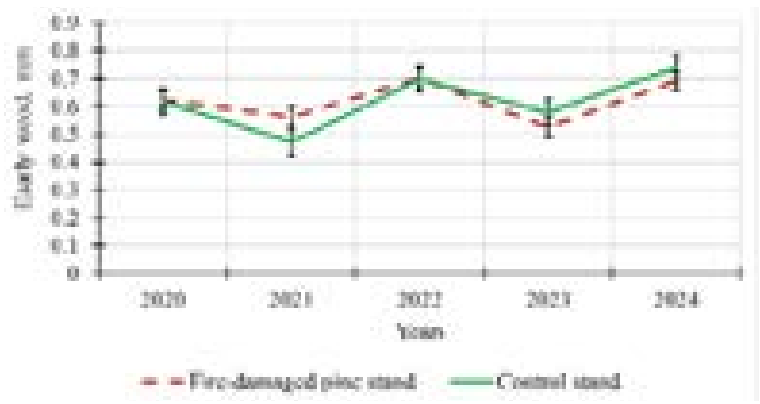


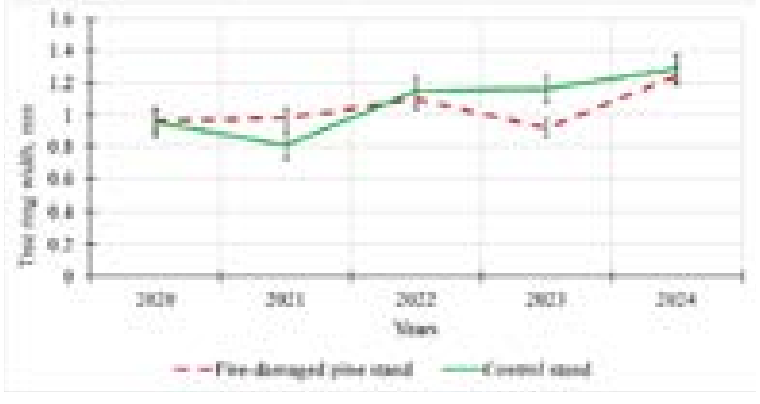
Fig. 4. Dynamics of radial growth of Scots pine on the fire-damaged plot in 2022 by sanitary condition categories



A) Dynamics of latewood layers in the fire-damaged stand and the control stand



B) Dynamics of earlywood layers in the fire-damaged stand and the control stand



C) Dynamics of annual ring layers in the fire-damaged stand and the control stand

Fig. 5. Dynamics of latewood, earlywood, and annual layers in the fire-damaged stand and the control stand

shallow, and the middle-aged pine stands have thick bark that protected the cambium, phloem, and conductive tissues of the wood from fire damage. Moreover, as a result of sanitary felling after the fire, 14% of the trees were lost, which improved light conditions and nutrient availability for the remaining trees.

Analysis of the latewood/earlywood ratio showed a decrease in this index for the damaged plot in the year of the fire (2022) and the first post-fire year (2023), indicating that this index is suitable for characterizing the impact of stress factors (fires, drought years, etc.) on the radial growth of Scots pine (Fig. 6).

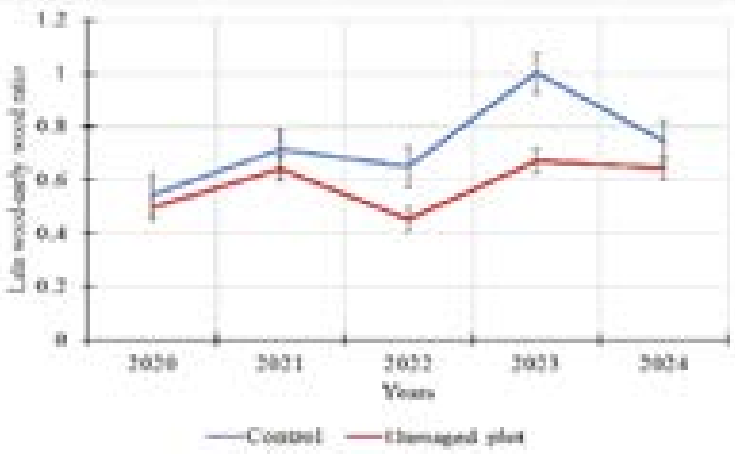


Fig. 6. Latewood/earlywood ratio

Latewood proved to be the most sensitive to changes in environmental conditions. A regression relationship between latewood indices and char height on the stems was established for the year of the fire (2022), which is described by a third-order curve (η=0.73±0.25, $t_{fact.}$= 2.87, $t_{theor.}$= 2.37, $t_{fact} > t_{reop}$ at the 0.05 significance level) (Fig. 7).

A regression relationship between latewood indices and char height on the stems was established for the year after the fire (2023), which is described by a third-order curve (η=0.78±0.25, $t_{fact.}$= 2.87, $t_{theor.}$= 2.37, $t_{fact.} > t_{theor.}$ at the 0.05 significance level) (Fig. 8).

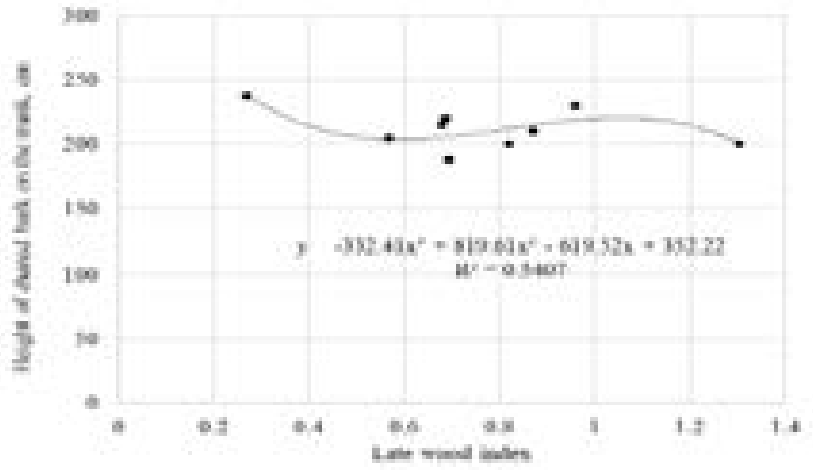


Fig. 7. Regression dependence of the late wood indices for 2022 (year of fire) and the height of the bark char on the trunks

Discussion

Our results are in good agreement with current understanding of fire effects on radial growth of various pine species in arid and Mediterranean regions. In particular, a study of *Pinus radiata* in the Jonkershoek Valley (Western Cape Province, South Africa), which has a Mediterranean-type climate with warm, dry summers and wet, mild winters, demonstrated a significant growth reduction directly in the year of the fire and the following year. Recovery of radial growth was expected as early as the second year after the fire, with a pronounced interaction between the degree of fire damage and precipitation amount. Importantly, char height on the stem – an indicator of scorching intensity – correlated with a significant narrowing of annual rings and a decrease in the latewood proportion [15].

In contrast, for Scots pine in young stands of the Left-Bank Forest-Steppe of Ukraine, the recovery process proved to be longer: after a surface fire in May 2011, the surviving trees were able to return to the radial growth level recorded before the disturbance only in the sixth year, during 2014–2016 [16,17]. Such differences in recovery time may be explained by both species-specific traits and differences in climatic conditions and fire severity.

It should be emphasised that fires not only directly cause local tissue necrosis, but also trigger a systemic stress response of the entire tree, which is reflected in the multi-year dynamics of annual ring width [18]. Dendrochronological studies reveal the ecophysiological mechanisms of such a response: for example, heavily defoliated trees not only reduce radial growth but also alter their water consumption regime due to significant crown damage [19]. In our case, we used sanitary condition categories that integrally characterise, among other things, the crown condition. It was

found that statistically significant recovery of annual wood increment after the fire was observed only in trees classified as Category 2 (weakened). In contrast, healthy trees (Category 1) were completely absent on the fire-affected plot.

Additional evidence of the decisive role of defoliation and drought is provided by results obtained for *Pinus pinaster* in hot and dry areas of the Mediterranean. Comparison of burned trees with significant crown deformation with undamaged specimens revealed a reduction in both radial growth and photosynthetic activity for three years after the fire. Monitoring of cambial activity showed that hot and dry periods exacerbated the negative effects: the affected trees decreased xylem production, delayed growth phenology, and reduced wood plasticity. This indicates that the combination of substantial photosynthetic limitations due to

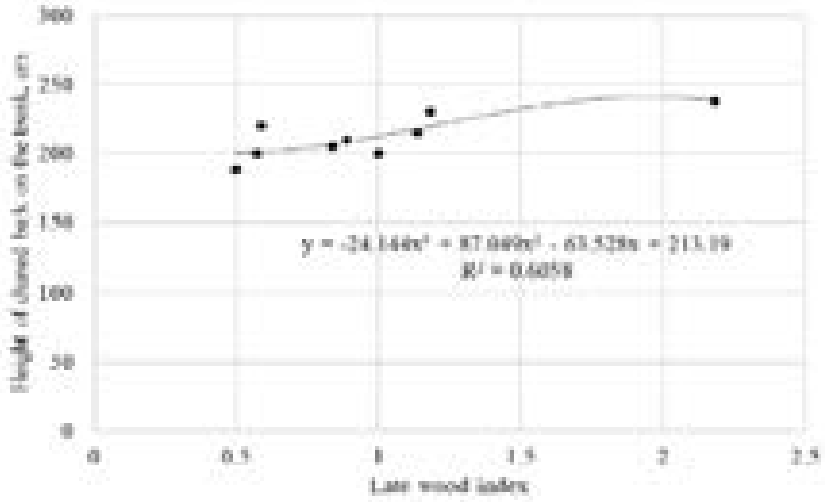


Fig. 8. Regression relationship between latewood indices for 2022 (the year of the fire) and char height on the stems

defoliation and recurrent droughts can lead to prolonged growth suppression and prevent the return of productivity to pre-disturbance levels. Similarly, other researchers emphasise that drought can exacerbate the negative effects of fires on growth [20]

At the same time, there are factors that mitigate stress effects. In particular, a reduction in intra- and interspecific competition after the loss of part of the stand can partially compensate for the adverse effects of warming by reducing moisture deficit due to lower overall resource consumption by neighbouring vegetation [21]. Moreover, fire resistance depends significantly on the species. For instance, data on *Pinus nigra* confirm its characteristic ability to withstand surface fires without critical consequences for growth [22]. In our case, middle-aged Scots pine trees have sufficiently thick bark so that, under conditions of shallow charring depth, even a char height of 200–250 mm on the stem did not cause dieback of the surviving individuals. Thus, the combination of species adaptations, reduced competition, and favourable weather conditions in the post-fire period determines the trajectory of radial growth recovery.

Conclusions

1. The period 2022–2024 was characterised by progressive thermal stress: the temperature deviation from the normal increased from 13% to 28%. The most extreme year was 2023 (precipitation deficit of 33%), which exacerbated the negative impact of the pyrogenic factor on radial growth.

2. The fire led to a complete loss of the healthy tree category on the damaged plot by 2024. The total mortality due to the fire and subsequent sanitary felling amounted to 14%.

3. Latewood proved to be the most sensitive indicator of fire: in the year of stress, its width decreased by 56% compared to the control (0.20±0.04 mm and. 0.45±0.08 mm). At the same time, earlywood and annual ring parameters did not show statistically significant changes.

4. In the second year after the fire (2024), the difference in latewood width between the plots disappeared. This confirms the high adaptive capacity of middle-aged Scots pines to restore radial growth provided the cambium remains viable.

5. The latewood/earlywood ratio has been proven to be a reliable marker of pyrogenic stress. The statistically significant regression relationship between latewood indices and char height (2022–2023) allows this indicator to be used for quantitative assessment of the degree of tree damage.

Внесок авторів: всі автори зробили рівний внесок у цю роботу
Конфлікт інтересів: автори засвідчують, що, незважаючи на те, що один із авторів статті є членом редакційної колегії цього журналу, процес рецензування, прийняття рішення щодо

Author Contributions: All authors contributed equally to this work
Conflict of Interest: The authors certifies that, although one of the authors of the article is a member of the editorial board of this journal, the peer review, publication decision, and editorial pro-

публікації та редагування проводилися незалежно, без його участі чи впливу. Будь-які потенційні конфлікти інтересів були повністю усунені шляхом зовнішнього контролю процесу.

Декларація про використання генеративного штучного інтелекту: Автори використовували інструменти генеративного штучного інтелекту (GenAI) для допоміжної роботи: моделі ChatGPT-5.5 (OpenAI, 2026) виключно для мовного редагування, структурного впорядкування тексту; Grammarly – для перевірки правильності перекладу тексту. Усі результати роботи з цими інструментами були ретельно контрольовані, перевірені та, за необхідності, відредаговані авторами. Весь науковий контент, матеріали та висновки були створені авторами. Автори несуть повну відповідальність за зміст та цілісність публікації.

cesses were conducted independently, without their participation or influence. Any potential conflicts of interest were fully mitigated through external oversight of the process.

Declaration of use of generative artificial intelligence: The authors utilized generative artificial intelligence (GenAI) tools in a supportive capacity: the ChatGPT-5.5 model (OpenAI, 2026) exclusively for language editing and structural text organization; Grammarly – to verify the correctness of the text translation. All outputs from these tools were carefully supervised, reviewed, and, where necessary, edited by the authors. All scientific content, materials, and conclusions were created by the authors. The authors retain full responsibility for the content and integrity of the publication.

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Вплив низової пожежі на радіальний приріст сосни звичайної в Поліських ландшафтах

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АНОТАЦІЯ

Лісові пожежі є одним із ключових дестабілізуючих чинників функціонування лісових екосистем, впливаючи на їх продуктивність, біорізноманіття та екосистемні послуги. В умовах кліматичних змін і посилення антропогенного навантаження, зокрема воєнних дій в Україні, частота та інтенсивність пожеж зростають, що зумовлює необхідність дослідження постпірогенних процесів у лісах Полісся. Метою роботи є – встановити особливості впливу низової пожежі на радіальний приріст сосни звичайної (*Pinus sylvestris* L.) у середньовікових деревостанах Поліських ландшафтів. Дослідження базується на поєднанні дендрохронологічного аналізу, методів лісової таксації та статистичної обробки даних. Відібрано керни з пошкодженого пожежею та контрольного насаджень. Побудовано локальні деревно-кільцеві хронології, застосовано індексацію з використанням ковзного згладжування. Виконано кореляційний і регресійний аналіз між показниками приросту та висотою нагару на стовбурі. Встановлено суттєве зниження радіального приросту у рік пожежі та наступний період, з максимальною депресією у 2023 році, що було посилено посушливими кліматичними умовами. Найбільш чутливим індикатором впливу пожежі виявилася пізня деревина, товщина якої у пошкодженому насадженні була достовірно меншою порівняно з контролем. Відновлення приросту відбулося протягом двох років для дерев, що зберегли життєздатність. Виявлено статистично значущу залежність між індексами пізньої деревини та висотою нагару. Ослаблені дерева (II категорії) демонстрували позитивну реакцію на зменшення конкуренції, тоді як сильно ослаблені – не відновлювали приріст. Досліджено вплив пожежі 2022 р. на середньовікові соснові насадження в умовах термічного стресу (відхилення температури +13–28%). Встановлено, що пізня деревина є найбільш чутливим індикатором пірогенного впливу: у рік пожежі її ширина скоротилася на 56% (до 0,20±0,04 мм), тоді як параметри ранньої деревини залишилися стабільними. Виявлено статистично значущу регресійну залежність між індексами пізньої деревини та висотою нагару. Доведено, що за умови збереження камбію дерева відновлюють радіальний приріст протягом двох років, що свідчить про їхню високу резистентність.

ІНФОРМАЦІЯ ПРО СТАТТЮ :

Рукопис надійшов
11 лютого 2026

Отримано після рецензування
17 березня 2026

Затверджено до друку
25 травня 2026

Опубліковано онлайн
30 травня 2026

Ключові слова:

радіальний приріст, Pinus sylvestris L., низова пожежа, дендрохронологія, пізня деревина, постпірогенна динаміка, Полісся, ландшафт, ліс, кліматичні зміни, санітарний стан дерев, біоіндикація.

https://doi.org/10.26565/2410-7360-2026-64-32

УДК 574.64:504.064

Комплексне дослідження небезпечних властивостей нафтовмісних відходів H14

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АНОТАЦІЯ

У статті розглянуто сучасні підходи до визначення небезпечної властивості відходів HP14 «екотоксичність» відповідно до вимог європейського законодавства та національних нормативних документів. Проаналізовано обмеження традиційної хімічної класифікації відходів, що базується на визначенні концентрацій окремих токсичних компонентів, зокрема у випадку складних багатокомпонентних матриць, таких як бурові шлами. Обґрунтовано доцільність поєднання фізико-хімічних методів аналізу з біотестуванням для більш об'єктивної оцінки потенційної екологічної небезпеки відходів. Експериментальні дослідження проведено на зразках бурових шламів із залишками бурового розчину, відібраних на свердловинах №150 та №152 Великобубнівського родовища (Сумська область). Виконано комплексну оцінку відходів за результатами санітарно-хімічних досліджень, визначено фізико-хімічні показники та вміст важких металів. За результатами хімічної оцінки сумарний вміст токсичних компонентів не перевищував встановлених нормативних порогів, що дозволило попередньо класифікувати відходи як такі, що не мають небезпечної властивості HP14. Подальше біотестування водних витяжок із використанням тест-організмів Ceriodaphnia affinis Lilljeborg показало наявність хронічної токсичності та віднесення відходів до 4 класу якості водних витяжок, що відповідає високому рівню екотоксичності (H410 – дуже токсично для водних організмів із довготривалими наслідками). Встановлено суттєву розбіжність між результатами хімічного аналізу та біологічною реакцією тест-організмів, що пояснюється комбінованою дією компонентів, біодоступністю токсикантів, наявністю неврахованих сполук та трансформацією речовин у водному середовищі. Отримані результати підтверджують необхідність обов'язкового застосування біотестування при класифікації відходів за показником екотоксичності та доцільність удосконалення підходів до оцінки небезпечних властивостей складних промислових відходів.

ІНФОРМАЦІЯ ПРО СТАТТЮ :

Рукопис надійшов
30 березня 2026

Отримано після рецензування
5 травня 2026

Затверджено до друку
25 травня 2026

Опубліковано онлайн
30 травня 2026

Ключові слова:

екотоксичність; бурові шлами; відходи буріння; біотестування; HP14; нафтовмісні відходи; екологічний ризик; класифікація відходів.

Вступ

Регламент Ради (ЄС) 2017/997 щодо небезпечної властивості HP 14 «екотоксичність» визначає основні критерії оцінки екотоксичності відходів.

Відходи класифікуються як «екотоксичні», якщо вони створюють або потенційно можуть створювати негайну чи відкладену загрозу для одного або декількох компонентів навколишнього природного середовища.

Основним підходом до хімічної класифікації відходів є так званий традиційний метод, який полягає у визначенні концентрацій речовин, віднесених до категорії екотоксичних відповідно до Регламенту (ЄС) № 1272/2008

Як цитувати : ХКрайнюков Олексій, Кривицька Іветта, Самохвалова Валентина, Проненко Максим (2026). Комплексне дослідження небезпечних властивостей нафтовмісних відходів H14. *Вісник Харківського національного університету імені В.Н. Каразіна Серія «Геологія. Географія. Екологія»*, (64), 415–423. https://doi.org/10.26565/2410-7360-2026-64-32

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(CLP – Classification, Labelling and Packaging of Substances and Mixtures). Розрахунок виконується із застосуванням спеціальних формул і встановлених порогових значень концентрацій, що дозволяє визначити рівень небезпечності суміші за принципом методу підсумовування.

Властивість HP14 також можна визначити шляхом проведення експериментальних випробувань на токсичність, процедури яких описані в Європейському регламенті 440/2008/ЄС або в «інших міжнародно визнаних методах та рекомендаціях щодо випробувань» (Регламент Ради 2017/997). У цьому випадку пріоритет надається екотоксикологічній класифікації над хімічною, але оскільки результати біологічних аналізів сильно залежать від підготовки зразків, досліджуваних організмів та прийнятих токсичних порогів (Частина 4, Додаток I, Європейський регламент 2008/1272/ЄС), суворе застосування фактичних нормативів викликає кілька проблем, пов'язаних не лише з методологічними процедурами, але й з інтерпретацією даних, що ускладнює порівняння результатів та класифікацію, особливо під час випробувань складних відходів та невизначених матриць [1].

Як звичайні, так і експериментальні методології на основі CLP розроблені для класифікації небезпечних речовин та сумішей відомих сполук, тоді як детальний хімічний склад відходів, як правило, невідомий. Таким чином, сукупний вплив на навколишнє середовище суміші забруднюючих речовин, що зазвичай присутні в більшості категорій відходів, недооцінюється. Тому класифікація базується на кодах небезпеки компонентів, які, як вважається, присутні в їхніх найбільш токсичних формах, відповідно до принципу «оцінки найгіршого випадку», що призводить до обережної практики управління, яка часто є нездійсненною та/або не є необхідною.

Для визначення екологічної небезпеки відходів згідно з критеріями CLP необхідно порівнювати результати екотоксикологічних випробувань із стандартами якості навколишнього середовища (EQS) та встановленими хімічними граничними значеннями для небезпечних речовин. Такий підхід дозволяє оцінити як короткострокові, так і довгострокові ризики, що можуть виникати внаслідок впливу відходів на довкілля. Водночас, для класифікації небезпечної властивості HP 14 («Екотоксичність») розмежування між гострою та хронічною токсичністю не є обов'язковим критерієм.

Крім того, результати екотоксикологічних досліджень можуть бути співставлені з пороговими значеннями водної токсичності, наведеними в Регламенті CLP, лише за умови, що біотестування проведене відповідно до методики водонакопичуваної фракції (WAF), описаної в рекомендаціях OECD 23/2000.

Згідно з цими вимогами, під час аналізу використовують малі проби відходів (1, 10, 100 мг), які, однак, не можуть повною мірою відображати властивості всієї партії зразка через його гетерогенний склад. Однією з основних умов є забезпечення повторюваності та відтворюваності результатів.

З огляду на це, слід розробити новий та адаптований підхід для стандартизованої класифікації відходів, який би став основою для екологічно сумісного управління з точки зору оцінки небезпеки. Процедура, описана у стандарті EN14735:2005, рекомендує використовувати елюати відходів для оцінки екотоксикологічних властивостей, що дозволяє отримати результати, що відповідають класифікації, зазначеній у Європейському переліку відходів, як показано [2].

Зі стрімким розвитком промисловості та постійним зростанням потреб людства у паливно-енергетичних ресурсах роль нафтопродуктів в сучасній економіці залишається надзвичайно важливою. За оцінками фахівців, щороку у світі споживаються мільярди тонн сирої нафти, і обсяги її використання продовжують зростати. Водночас на всіх етапах її життєвого циклу – від видобутку й транспортування до зберігання та переробки – утворюється значна кількість нафтовмісних шламів та інших відходів [3, 4].

Особливо гостро ця проблема проявляється у країнах із розвиненою нафтогазовою промисловістю. Так, у Китаї щорічно утворюється понад 6 мільйонів тонн нафтовмісних шламів, що становить більше 10 % їх світового обсягу [5]. Такі відходи містять значну кількість залишкових нафтових вуглеводнів, а також токсичні органічні сполуки, зокрема бензольного ряду, які здатні негативно впливати на стан ґрунтів, поверхневих і підземних вод, атмосферного повітря та живих організмів [6, 7]. Саме тому пошук ефективних і екологічно безпечних методів їх переробки та утилізації є одним із пріоритетних напрямів сучасних наукових досліджень як у усьому світі, так і в Україні.

Склад нафтовмісного шламу надзвичайно складний та різноманітний, з сильними токсичними характеристиками, що становлять значну загрозу для екосистем. Після потрапляння в природне середовище шлам, що містить нафтопродукти може спричинити серйозні наслідки забруднення екосистем [8]. Для вирішення проблем забруднення навколишнього середовища, спричинених нафтовмісним шламом, сучасні заходи очищення в першу чергу зосереджені на таких підходах: технологія піролізу, мікробна ремедіація, нешкідлива обробка на основі коксування, технологія термічного промивання-іммобілізації [9] та технологія

екстракції розчинниками [10-13]. Серед них технологія піролізу вважається дуже перспективною завдяки високій ефективності вилучення сирої нафти та газу, відносно низькому негативному впливу на навколишнє середовище та ретельному очищенню забруднюючих речовин. Отже, вона стала основним методом боротьби із забрудненням нафтовмісним шламом [14, 15]. Піроліз нафтовмісного шламу призводить до утворення залишків піролізного нафтовмісного шламу, який стає основним твердим відходом. В останні роки дослідження щодо використання ресурсів залишків піролізного нафтовмісного шламу зростають на міжнародному рівні, причому обробка затвердінням стала переважним методом обробки таких залишків. Зокрема, обробка затвердінням включає змішування матеріалів, що затвердівають, із залишками нафтогазових шламів, доповнених відповідними добавками, для сприяння складним фізико-хімічним реакціям. Це прискорює утворення твердої речовини, іммобілізуючи токсичні та шкідливі компоненти для зменшення екологічної небезпеки. Після затвердіння нафтогазовий шлам може бути перетворений на затверділі блоки певної міцності, які можна безпосередньо використовувати для приготування фундаментних матеріалів будівель, безпечно захоронювати на звалищах або навіть застосовувати в інженерних проектах, таких як дорожнє покриття [16].

Існує кілька підходів до характеристики токсичності відходів і різних видів продукції. Один із найпоширеніших методів ґрунтується на хімічному аналізі, що передбачає визначення концентрацій окремих забруднювальних речовин – так звану оцінку елементного складу.

Однак аналіз біодоступних елементів і органічних забруднювачів у зразках зі складним або невідомим хімічним складом є значно складнішим завданням. Для виділення та концентрування органічних сполук, які зазвичай присутні у дуже низьких концентраціях, необхідно застосовувати кілька етапів екстракції з використанням різних методик.

Складність суттєво зростає, коли йдеться про комплексні матриці, такі як осади стічних вод, ґрунти чи компости, де присутні численні взаємодіючі компоненти.

Звичайні хімічні методи аналізу в таких випадках мають обмежені можливості, оскільки отримані дані не завжди адекватно відображають реальний екотоксикологічний потенціал зразка. Це може призвести до помилкової оцінки токсичності, адже хімічні взаємодії між сполуками та їхній сукупний вплив на навколишнє середовище часто залишаються поза межами виявлення традиційних методів [17].

Ефективна оцінка небезпечних властивостей відходів має базуватися на поєднанні хімічних і біологічних методів аналізу, що забезпечить більш повне уявлення про потенційний екологічний ризик. У випадках, коли визначення всього спектра небезпечних хімічних речовин або стійких органічних забруднювачів у складі відходів є неможливим чи обмеженим, доцільно застосовувати виключно метод біотестування, який дозволяє безпосередньо оцінити сумарний токсичний ефект відходів на біоту.

Результати, отримані при дослідженні токсичних властивостей різних типів бурових шламів та присвоєння їм відповідних Н-кодів на основі цих даних підтверджують доцільність і необхідність впровадження методу біотестування у систему класифікації відходів [18].

Мета. У цьому дослідженні проведено опрацювання інноваційної процедури з визначення небезпечних властивостей відходів HP14, що містять нафтові сполуки.

Методи

З метою визначення небезпечних властивостей відходів буріння - бурових шламів з залишками бурового розчину, що утворилися на свердловинах №№ 150 та152 Великобубнівського родовища, Сумська область та їх класифікації була проведена комплексна оцінка відходів за результатами санітарно-хімічних досліджень з урахуванням токсикологічних характеристик складових відходів та їх біотестування. Дослідження було проведено відповідно до Додатку 3 Закону України «Про управління відходами» та Порядку класифікації відходів, затвердженого Постановою Кабінету Міністрів України від 20.10.2023 р. №1102.

Експериментальні дослідження небезпечних властивостей відходів було проведено у грудні 2025 року в лабораторії еколого-токсикологічних досліджень ННІ екології, зеленої енергетики та сталого розвитку.

Лабораторія еколого-токсикологічних досліджень ННІ екології, зеленої енергетики та сталого розвитку за результатами аудиту ДП «Харківстандартметрологія» відповідає вимогам ДСТУ ISO 10012:2005 на проведення вимірювань токсичності методом біотестування у сфері поширення державного метрологічного нагляду (свідоцтво про відповідність системи вимірювань ДСТУ ISO 10012:2005 № 01-0132/2025 від 04 грудня 2025 р., чинно до 05 грудня 2028 року).

Результати. На першому етапі дослідження для експериментів були відібрано бурові шлами з двох свердловин, що дало змогу врахувати варіації компонентного складу та можливі відмінності у рівнях токсичної дії на тестові організми під час біотестування.

Проба відходів буріння – бурові шлами з залишками бурового розчину за візуальним ог-

Таблиця 1 / Table 1

Фізико-хімічні показники зразків відходів буріння – бурових шламів з залишками бурового розчину, які було відібрано з ємності для зберігання відходів на свердловинах №№ 150, 152 Великобубнівського родовища / Physicochemical parameters of drilling waste samples – drilling sludge with residual drilling fluid – collected from waste storage tanks at wells No. 150 and 152 of the Velykobubnivske oil field

Назва проби	pH, абс.од.	% вологості	Вміст органічної складової, %	Вміст мінеральної складової, %	Вміст SiO_2, %	Вміст CaO, %	Вміст MgO, %	Вміст нафто- продуктів, %
№150	11,0	40,0	9,59	90,41	59,99	25,6	4,81	0,099
№152	10,0	44,0	10,5	86,60	57,85	24,5	4,25	0,086

Таблиця 2 / Table 2

Вміст важких металів у відходах буріння – бурових шламах з залишками бурового розчину, відібраних з ємності для зберігання відходів на свердловинах №№. 150, 152 Великобубнівського родовища / Content of heavy metals in drilling waste – drilling sludge with residual drilling fluid – collected from waste storage tanks at wells No. 150 and 152 of the Velykobubnivske oil field

Назва проби	Вміст важких металів та інших компонентів, мг/кг									
	Pb	Cu	Ni	Cr	Co	Cd	Zn	Mn	Fe	Al
№150	1,72	26,83	9,04	12,30	3,2	2,36	62,21	274,64	1760,0	1112,14
№152	1,56	27,65	12,06	11,30	5,32	3,65	75,98	290,32	2000,12	1121,52

лядом – волога пастоподібна маса світло-сірого кольору, без специфічного запаху.

Результати фізико-хімічних досліджень відходів буріння подано у таблиці 1 та результати визначення вмісту важких металів у відходах буріння наведено у таблиці 2.

Згідно з результатами проведених досліджень (табл. 1, 2) відходів з свердловини №150 Великобубнівського родовища, сумарна концентрація мінеральних речовин складає 90,41 %, з них сумарна концентрація токсичних речовин I класу (Pb, Cd, Cr) не досягала порогових значень та складала – 0,001638 < 0,1, речовин II класу (Cu, Mn, Ni, Co) не досягала порогових значень та складала – 0,031371 % < 0,25 %, хімічних речовин III класу (Zn, Fe) - 0,18222 < 5 %, IV класу токсичності (Si, Mg, Ca, Al) – 90,19 % - речовини, які не завдають гострої токсичності при пероральному надходженні в організм [21].

Таким чином, за результатами досліджень встановлено, що бурові шлами з залишками бурового розчину, відібрані з ємності для зберігання відходів свердловини №150 Великобубнівського родовища, є вологою пастоподібною субстанцією з вмістом лужних сполук металів (pH – 11,0 одиниць активності); сумарна концентрація токсикантів I, II, III і IV класів токсичності, визначених за ознаками небезпечного впливу складових бурових шламів з залишками бурового розчину при пероральному надходженні в організм значно менша за лімі-ти концентрацій небезпечного впливу відповідних категорій небезпеки.

Відповідно до результатів (табл. 1, 2) проведених експериментальних досліджень відходів зі свердловини № 152 Великобубнівського родовища встановлено, що сумарний вміст мінеральних компонентів становить 86,60 %. Серед них концентрація токсичних елементів I класу небезпеки (Pb, Cd, Cr) є нижчою за порогові значення та становить 0,0016575,98 % < 0,1 %. Рівень речовин II класу (Cu, Mn, Ni, Co) також не перевищує нормативних лімітів і дорівнює 0,0335 % < 0,25 %.

Вміст хімічних елементів III класу (Zn, Fe) становить 0,207 % < 5 %, а речовини IV класу токсичності, мінеральна основа - (Si, Mg, Ca) утворюють основну частину складу – 86,60 %, що свідчить про відсутність гострої токсичної дії при пероральному надходженні в організм [21].

Відповідно до результатів санітарно-хімічного аналізу бурові шлами зі свердловини № 152, які було відібрано з ємності зберігання відходів, являють собою волого-пастоподібну субстанцію з підвищеною лужністю (pH = 10,0), обумовленою наявністю лужних сполук металів. Сумарна концентрація токсикантів I–IV класів токсичності, визначених за показниками потенційного небезпечного впливу складових бурових шламів при пероральному надходженні в організм, є суттєво нижчою за граничні концентрації, встановлені для відповідних категорій небезпеки.

Виходячи з отриманих результатів можна констатувати, що сумарна масова частка у обох зразків відходів, речовин I–III класів токсичності була менша за 25 %, тобто відходи не мали властивості «екотоксичність» (HB14) і вважаються за Порядком класифікації відходів – як відходи «не небезпечні».

Такий первинний висновок ми зробили виходячи з результатів фізико-хімічних досліджень, які на нашу думку не повністю характеризують можливий негативний вплив бурових шламів на біологічні системи, зважаючи на те, що «токсичні властивості - це здатність речовини або чинника викликати шкідливий вплив на живі організми» і визначення таких властивостей необхідно проводити за допомогою живих тест-систем.

Відповідно до [20, 22] за екотоксичністю класифікують відходи як небезпечні, якщо вони відповідають наступним умовам: відходи, що містять одну або кілька речовин, класифікованих як хронічно токсичні для водних біоресурсів та віднесені до кодів H410, H411 або H412.

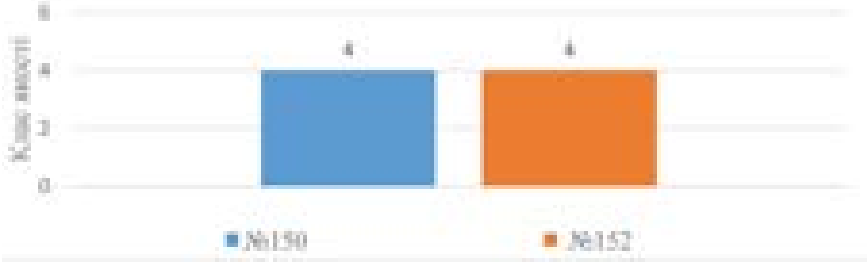


Рис. 1. Результати визначення класу якості водних витяжок з бурових шламів, які було відібрано з ємностей для зберігання відходів на свердловинах №№ 150, 152 Великобубнівського родовища /
Fig. 1. Results of determining the quality class of aqueous extracts from drilling sludge sampled from waste storage tanks at wells No. 150 and 152 of the Velykobubnivske oil field

- H410: Дуже отруйно для водяних організмів, із тривалими наслідками;
- H411: Отруйно для водяних організмів, із тривалими наслідками;
- H412: Шкідливо для водяних організмів, із тривалими наслідками.

Для підтвердження чи спростування розбіжності між фізико-хімічною оцінкою та біологічною реакцією на наступному етапі досліджень було проведено серію експериментів задля визначення токсичних властивостей відходів, які було відібрано з ємностей для зберігання відходів з свердловин №№ 150, 152 Великобубнівського родовища.

У ході проведення дослідження було застосовано методику з визначення хронічної токсичності хімічних речовин та відходів із використанням тест-організмів – ракоподібних *Ceriodaphnia affinis* Lilljeborg. Критерієм виявлення хронічної токсичності досліджуваних зразків вважалося статистично достовірне зниження рівня виживаності та/або плодючості *Ceriodaphnia affinis* Lilljeborg у дослідних серіях порівняно з контролем протягом усього періоду біотестування. Тривалість експерименту становила близько 7 діб або до моменту, коли у 80 % особин контрольної групи відбувалося народження трьох пометів [23].

В результаті проведеного біотестування встановлено (рис. 1), що зразки бурових шламів відповідають 4 класу якості (ступінь забрудненості водної витяжки – брудна). Такі результати дають змогу зафіксувати небезпечні властивості відходів та віднесення їх до H410: Дуже отруйно для водяних організмів, із тривалими наслідками.

Дискусія

Виходячи з отриманих результатів, встановлено суттєву розбіжність між оцінкою за хімічним складом і біологічною реакцією. Причини такої розбіжності можуть бути наступні:

- сумісна дія речовин: навіть при низьких концентраціях кілька різних сполук разом можуть чинити значний токсичний ефект;
- наявність неврахованих компонентів у складі відходів: хімічний аналіз охоплює лише визначені (відомі) речовини, а відходи часто містять «невидимі» домішки – полімери, органічні залишки, ПАР тощо;
- різна біодоступність: деякі хімічні сполуки можуть утворювати рухомі, легкорозчинні форми, які активно поглинаються біотою, хоча їх загальна масова частка мала;
- зміна форми хімічних сумішей у водному середовищі: при контакті з водою чи киснем можуть утворюватися токсичні оксидні або іонні форми (наприклад, Cr (VI) із Cr (III)).

Якщо результати біотестування свідчать про токсичність, навіть за низьких концентрацій токсикантів, відходи будуть вважатися небезпечними за ознакою HB14 «екотоксичність», що закріплено у Порядку класифікації відходів (Постанова КМУ №1102 від 20.10.2023 р.) та Регламенті ЄС 2017/997.

За таких обставин відходи мають бути тимчасово віднесені до небезпечних до уточнення результатів, а саме:

- проводиться повторне або розширене біотестування (з іншим тест-об'єктом – водоростями, рибами);
- виконується додатковий хімічний аналіз (на органічні токсиканти, феноли, ПАР, поліароматичні вуглеводні);
- при повторному підтвердженні токсичності – класифікуються як небезпечні за властивістю HB14.

Отримані результати узгоджуються з висновками наведеними у роботі [2], де зазначається, що класифікація небезпечної властивості HP14, заснована виключно на визначенні концентрацій окремих токсичних компонентів, не завжди відображає реальний рівень екологічної небезпеки відходів. Автор підкреслює, що застосування екотоксикологічних тестів дозволяє врахувати сукупний вплив складних багатокомпонентних сумішей та підвищує достовірність оцінки екотоксичності.

Подібні результати отримані також у роботі [1], де встановлено, що біотестування елюатів відходів із використанням біологічних тест-систем виявляє токсичний ефект навіть у тих випадках, коли концентрації окремих забруднювачів не перевищують нормативних значень. Це свідчить про важливу роль синергетичної дії компонентів суміші та необхідність комплексної оцінки екологічного ризику.

Крім того, результати проведеного дослідження узгоджуються з попередніми роботами Крайнюкова та співавторів [18], у яких було показано, що використання методу біотестування дозволяє більш об'єктивно оцінювати небезпечні властивості промислових відходів і виявляти приховану екотоксичність, яка не визначається традиційними фізико-хімічними методами аналізу. Отримані дані підтверджують доцільність впровадження інтегрованого підходу, що поєднує результати хімічного аналізу з біологічними дослідженнями, для підвищення достовірності класифікації відходів за властивістю HP14.

Отримані результати узгоджуються з дослідженнями українських науковців, присвячених застосуванню біотестування у системі екологічного моніторингу. Так, Д. М. Саламатін та С. В. Дігтяр [24] встановили, що використання тест-організмів *Daphnia magna* дозволяє виявляти токсичну дію природних, поверхневих та промислових стічних вод навіть у випадках, коли результати традиційного фізико-хімічного аналізу не свідчать про суттєве перевищення нормативних показників. Автори наголошують, що біотестування є важливим інструментом інтегральної оцінки якості довкілля та доцільно доповнює стандартні методи екологічного контролю.

Висновки

1. Результати дослідження свідчать, що класифікація відходів буріння лише за фізико-хімічними показниками може не відображати їх реальний екотоксикологічний потенціал. Незважаючи на те, що концентрації токсичних компонентів у досліджених бурових шламах не перевищували встановлених нормативних порогів, біотестування водних витяжок із використанням тест-організмів *Ceriodaphnia affinis* виявило прояви хронічної токсичності. Це підтверджує наявність небезпечної властивості HP14 («екотоксичність») та демонструє суттєву розбіжність між результатами хімічного аналізу і біологічною реакцією тест-систем.

2. Ймовірними причинами такої невідповідності є сумарна дія кількох забруднювачів, наявність неврахованих компонентів складної матриці відходів, відмінності у біодоступності токсикантів і можливі трансформації хімічних сполук у водному середовищі. Це підкреслює необхідність використання інтегрованого підходу до оцінки небезпечних властивостей відходів, який поєднує хімічні методи аналізу з біотестуванням.

3. Застосування біоіндикаційних методів дозволяє більш об'єктивно оцінювати екологічний ризик, своєчасно ідентифікувати потенційно небезпечні відходи та забезпечувати екологічно безпечне управління ними. Отримані результати підтверджують доцільність впровадження стандартизованих процедур біотестування у систему класифікації відходів відповідно до сучасних європейських і національних нормативних вимог.

Внесок авторів: всі автори зробили рівний внесок у цю роботу

Конфлікт інтересів: автори засвідчують, що, незважаючи на те, що один із авторів статті є членом редакційної колегії цього журналу, процес рецензування, прийняття рішення щодо публікації та редагування проводилися незалежно, без його участі чи впливу. Будь-які потенційні конфлікти інтересів були повністю усунені шляхом зовнішнього контролю процесу.

Декларація про використання генеративного штучного інтелекту: Автори використовували інструменти генеративного штучного інтелекту (GenAI) для допоміжної роботи: моделі ChatGPT-5.5 (OpenAI, 2026) виключно як допоміжний інструмент для мовного редагування та під час оформлення списку використаних джерел. Усі результати роботи з цими інструментами були ретельно контрольовані, перевірені та, за необхідності, відредаговані авторами. Весь науковий контент, матеріали та висновки були створені авторами. Автори несуть повну відповідальність за зміст та цілісність публікації.

Author Contributions: All authors contributed equally to this work

Conflict of Interest: The authors certifies that, although one of the authors of the article is a member of the editorial board of this journal, the peer review, publication decision, and editorial processes were conducted independently, without their participation or influence. Any potential conflicts of interest were fully mitigated through external oversight of the process.

Declaration of use of generative artificial intelligence: The authors utilized generative artificial intelligence (GenAI) tools in a supportive capacity: the ChatGPT-5.5 model (OpenAI, 2026) was used exclusively as an auxiliary tool for language editing and when compiling a list of used sources. All outputs from these tools were carefully supervised, reviewed, and, where necessary, edited by the authors. All scientific content, materials, and conclusions were created by the authors. The authors retain full responsibility for the content and integrity of the publication.

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Comprehensive Investigation of the HP14 Hazardous Property of Oil-Contaminated Wastes

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ABSTRACT

Introduction. The assessment of hazardous properties of industrial waste, particularly ecotoxicity (HP14), is a key element of environmental safety and sustainable waste management. Conventional chemical classification methods based on the determination of individual toxic components often fail to adequately reflect the real ecological risk of complex multicomponent waste matrices. This is especially relevant for oil-containing drilling sludge generated during oil extraction and processing. Therefore, the aim of this study was to evaluate the ecotoxic properties of drilling waste containing petroleum residues using both physicochemical analysis and biological testing in accordance with EU Regulation 2017/997 and relevant Ukrainian regulatory requirements.
Methods. Samples of drilling sludge containing residual drilling fluid were collected from wells No. 150 and 152 of the Velykobubnivske oil field (Sumy region, Ukraine). Physicochemical characterization included determination of pH, moisture content, mineral and organic fractions, petroleum hydrocarbon content, and concentrations of heavy metals. Hazard classification based on chemical composition was performed according to national waste classification procedures. To assess biological toxicity, chronic toxicity bioassays were conducted using the aquatic crustacean Ceriodaphnia affinis as a test organism. Toxicity criteria included statistically significant reductions in survival and reproduction compared with control groups over approximately seven days.

ARTICLE INFO

Manuscript received
2 March 2026

Revised manuscript received
8 May 2026

Manuscript accepted
25 May 2026

Available online
30 May 2026

Keywords:

ecotoxicity; drilling sludge; drilling waste; biotesting; HP14; oil-containing waste; environmental risk; waste classification.

Results. Physicochemical analysis showed that both waste samples consisted predominantly of mineral components with alkaline pH values (10–11) and relatively low concentrations of heavy metals. The total content of toxic substances of hazard classes I–III was below established regulatory thresholds, which initially indicated the absence of the hazardous property HP14. However, bioassay results revealed chronic toxicity of aqueous extracts corresponding to water quality class 4 (polluted). The observed biological response indicated significant ecotoxic effects despite low measured concentrations of individual toxicants. This discrepancy is likely due to combined effects of multiple contaminants, the presence of unaccounted organic compounds, differences in bioavailability, and chemical transformations occurring in aqueous environments.
Conclusions. The study demonstrates that chemical analysis alone may underestimate the ecological hazard of complex industrial wastes such as drilling sludge. Bioassay results provided evidence of ecotoxicity not predicted by physicochemical data, highlighting the importance of integrated assessment approaches combining chemical and biological methods. Implementation of standardized biotesting procedures is recommended for reliable classification of waste according to HP14 criteria and for environmentally sound waste management decisions. Such integrated methodologies can improve ecological risk assessment, support regulatory compliance, and enhance environmental protection in areas affected by oil industry activities.

In cites: Krainiukov Oleksii, Kryvytska Ivetta, Samokhvalova Valentyna, Pronenko Maksym (2026). Comprehensive Investigation of the HP14 Hazardous Property of Oil-Contaminated Wastes. *Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology*, (64), 415–423. https://doi.org/10.26565/2410-7360-2026-64-32 [In Ukrainian]

https://doi.org/10.26565/2410-7360-2026-64-33

UDC 911.3:551.4

River systems of the Volyn region: status, problems, and ways of preservation

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ABSTRACT

Introduction. River systems of the Volyn region are important components of the natural environment, ensuring the functioning of aquatic ecosystems, the formation of the hydrological regime of the territory, and the satisfaction of the needs of the population and the economy in water resources. Under current climate change and increasing anthropogenic pressure, they are undergoing significant transformations, manifested in changes in the hydrological regime, deterioration of water quality, and degradation of natural ecosystems. This necessitates their comprehensive ecological assessment, identification of key influencing factors, and development of effective approaches to water resource conservation and rational use.
Purpose. The aim of the study is a comprehensive assessment of the ecological status of river systems in the Volyn region under current environmental conditions, identification of the main threats to aquatic ecosystems, analysis of the level of anthropogenic load, and substantiation of scientific and practical approaches to their conservation and sustainable use.
Relevance. The relevance of the study is driven by the increasing anthropogenic pressure on small river basins associated with agricultural development, land reclamation, urbanization, and other economic activities. This leads to disruption of natural runoff formation processes, degradation of aquatic ecosystems, loss of biodiversity, and deterioration of water quality. These problems are particularly acute in the Polissya region and the forest-steppe zone of Volyn.
Methods. The study applies a set of general scientific and specialized methods, including comparative geographical analysis to identify spatial differences, mathematical statistics for data processing and interpretation, cartographic analysis for mapping basin structure, field observations for primary data collection, and synthesis. The research is based on integrated methodological approaches, including genetic, historical, systemic, and basin-based frameworks.
Results. The study provides a systematic analysis of the current state of river basin systems in Volyn and identifies the types and intensity of anthropogenic pressure on low-flow watercourses. Both qualitative and quantitative indicators of anthropogenic impact were established, and a system of indices for assessing the degree of environmental transformation was developed. An evaluation of the ecological status of water bodies was conducted, revealing key trends in their changes.
Novelty. The scientific novelty lies in the development and improvement of methodological approaches for analyzing and assessing anthropogenic transformations in small river catchments, enabling more accurate determination of ecological change levels and forecasting the further development of river systems.
Practical significance. The results can be used to improve water resource monitoring systems, develop environmental protection measures, enhance water management

ARTICLE INFO

Manuscript received
23 January 2026

Revised manuscript received
28 April 2026

Manuscript accepted
25 May 2026

Available online
30 May 2026

Keywords:

anthropogenic load; river runoff; river basin; ecological status; natural environment; pollution; sustainable water use; water resources; hydroecology; environmental monitoring.

In cites: Melniychuk Mykhailo, Myskovets Iryna, Sokol Mariana (2026). River systems of the Volyn region: status, problems, and ways of preservation. *Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology*, (64), 424–436. https://doi.org/10.26565/2410-7360-2026-64-33



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efficiency, and ensure the rational use of water resources in various sectors of the economy.

Discussion. The study analyzes natural, climatic, and physical-geographical factors influencing river runoff formation, assesses the impact of key economic sectors on aquatic ecosystems, and identifies major degradation drivers. A set of measures aimed at reducing anthropogenic pressure, improving water quality, and restoring the natural functioning of river systems is proposed

Introduction

Water resources, particularly rivers, are among the most important natural resources. They are easily accessible and widely used as sources of water supply and recreation for the population. Recently, environmental problems have been exacerbated by intensive water pollution, reduced water availability, river regulation, and the degradation of coastal strips and wetland ecosystems. Such changes disrupt the natural functions of rivers, pose risks to public health, and hinder the sustainable development of the region, necessitating a comprehensive analysis of Volyn's water assets, the identification of threats, and the development of an effective strategy for their preservation.

River waters are highly sensitive to changes occurring in the atmosphere, lithosphere, and Earth's surface due to economic activity. River waters and their condition are affected by the construction of reservoirs, residential and industrial buildings, and the introduction of central water consumption in cities and towns. The modern world lives in conditions of constant change, which is a consequence of the interaction between economic activity and the natural environment. Environmental crises affect both the global and regional levels. Hydrological problems are among the most pressing issues in natural resource management. River water resources are a key element of natural resource use, influencing the nature of economic activity and often limiting it. Groundwater distribution in Ukraine varies significantly, mainly due to natural conditions. The use of river water leads to changes in the hydrological regime and deterioration of water quality in natural water bodies. In addition, in conditions of global warming, the consumption of clean fresh water is increasing. Therefore, it is becoming increasingly important to study the current conditions of river water resources formation, water quality, and water use issues. The topic of the work is consistent with the priorities of scientific and technical development in the conditions of martial law in Ukraine (direction 5 "rational use of natural resources"), approved by Law of Ukraine No. 5534-1X of 21.12. 2023; the Action Plan for Environmental Protection for 2023-2025, approved by the Order of the Cabinet of Ministers of Ukraine No. 443-r dated April 21, 2021; "Water Strategy of Ukraine for the period up to 2050," approved by the order of the Cabinet of Ministers of Ukraine dated December 9, 2022, No. 1134-r.

The development of productive sectors should be based on the rational use of river waters and natural resources, strengthening their protection and efficiency in order to ensure comfortable conditions for the population to live, work, and relax.

Proper consideration of river water forecasts makes it possible to regulate them both in natural conditions and in conditions affected by economic activity, implementing scientifically based measures to improve the conditions for their formation.

The current state of research on the issue, with an analysis of the main works. There are many methods for monitoring and assessing the condition of river waters, including comprehensive studies of water resources in the Volyn region. Scientific publications from various years indicate that anthropogenic pressure on the region's river waters increased sharply in the 1960s and 1970s and is associated with drainage reclamation and other works.

The issue of preserving Ukraine's river ecosystems is discussed in scientific publications by domestic and foreign researchers. In particular, studies by V. I. Osadchy, S. I. Prokopenko, and L. M. Shevchuk analyzed the hydrological regime of Ukrainian rivers, taking into account anthropogenic influences, climate change, and water use [14;15;23]. Research by M. M. Grebenyuk, N. A. Vovk, M. R. Zabokrytska, A. P. Pashkov, and others is devoted to studying water quality and pollution in river systems, in particular the accumulation of heavy metals, organic substances, and agrochemicals in water and bottom sediments [5; 6; 10;11;13; 18; 19; 20].

General characteristics of Ukraine's river water resources, directions and types of their comprehensive use and protection can be found in reference literature [12], as well as in the studies of A.V. Yatsyk [13; 14]. In connection with the growth of anthropogenic impact on water bodies in Ukraine, research into the problems of surface runoff formation has intensified. These issues are covered in the works of E.D. Gopchenko, V.I. Vyshnevsky, Y.O. Molchak, V.K. Khilchevsky, and V.V. Grebenya [1; 2; 13; 14; 15; 16; 17; 18; 19]. Hydroecological problems of rivers, hydrochemical characteristics of water composition, and the specifics of channel processes are presented in scientific publications and monographs by O. G. Obodovsky, S. G. Pankevich, A. V. Yatsyk,

V. K. Khilchevsky, and V. I. Osadchy [1; 2; 20; 21]. Basic concepts, terms, and data on water objects are provided in reference publications and textbooks. Scientists focus particularly on the protection and restoration of water resources in small and medium-sized watercourses, the number of which is constantly decreasing due to the canalization of riverbeds and the regulation of flow. Many publications by A. V. Yatsyk, V. K. Khilchevsky, M. O. Klymenko, I. P. Kovalchuk, and M. R. Zabokrytska justify water use measures aimed at improving the ecological condition of river basins and individual administrative districts [4; 12; 22; 23; 13]. Geoecological problems of medium river flows in Ukraine are widely represented in sectoral studies by I.Y. Myskovets, A.P. Pashkova, and Y.O. Molchak [7; 18; 20]. An analysis of the ecological quality of surface waters in the river basins of the Western region is presented in the works of L. G. Chyzhevska, Y. O. Molchak, M. R. Zabokrytska, I. M. Netrobchuk, N. M. Gulieva, and P. V. Pysarenko [24; 5; 7; 9; 10; 23]. The impact of drainage reclamation on floodplain and riverbed processes and the state of surface waters has been analyzed in the works of O.G. Obodovsky [2] and V.O. Fesyuk [10]. At the end of the XXth and beginning of the XXIst centuries, scientists focused their attention on studying river basin problems.

The basin approach to studying surface waters is currently a priority scientific direction. The main theoretical and methodological aspects of studying surface waters in medium- and large-scale river basins in Ukraine are outlined in the works of V. I. Vyshnevsky, A. V. Yatsyk, Y. O. Molchak, M. O. Klymenko, and I. P. Kovalchuk [15; 22; 24; 25; 7; 18; 14]. Many publications focus primarily on assessing anthropogenic impact and analyzing the effects of drainage reclamation. Foreign researchers such as M. Meybeck, B. Moss, and A. Allan [26; 27; 28; 30; 31] emphasize the importance of preserving river ecosystem services, the role of integrated water resources management (IWRM), and the participation of local communities in monitoring and preservation activities. However, adapting such approaches to Ukrainian realities requires further research and adaptation to the local socio-economic and natural context.

Identification of previously unresolved parts of the problem. Despite the existence of a solid theoretical basis, most studies focus on individual aspects of the problem and do not provide a comprehensive view of the state of Volyn's rivers as an interconnected natural environment. The lack of a unified integrated model for assessing environmental risk for river systems in the region indicates the need for further interdisciplinary research using modern methods of spatial analysis, bioindication, and socio-ecological forecasting. Despite a significant number of studies devoted to the hydrological and ecological characteristics of river systems in Ukraine, the issue of water resources in the Volyn region remains insufficiently explored in scientific discourse. Most existing studies focus on general aspects of water use, the physical and chemical composition of water, or specific anthropogenic impacts, but there is no comprehensive interdisciplinary analysis that would simultaneously take into account the environmental, social, economic, and legal factors of river ecosystem degradation in Volyn. Issues related to the hydrological regime of small watercourses, the loss of the natural self-cleaning capacity of water bodies, and the degradation of coastal protection strips and wetlands, which are crucial for maintaining the region's water balance, remain insufficiently studied. In addition, the effectiveness of existing environmental protection programs and strategies for the conservation of Volyn's aquatic ecosystems, particularly at the local level, has not been properly evaluated. There is also a lack of empirical studies in contemporary scientific literature based on long-term monitoring of river systems in the region using geoinformation technologies, bioindication, and ecosystem service assessment. All these factors complicate the development of an effective strategy for managing Volyn's water resources based on the principles of sustainable development.

Defining the article's objective. The objective of the study is to conduct a comprehensive analysis of the ecological state of rivers in the Volyn region under current conditions, identify key threats to their functioning, and justify directions for conservation and sustainable use.

Materials and methods. The work utilised materials from the Kovel Hydrogeological and Land Reclamation Expedition, the Regional Water Resources Office in Volyn Oblast, the Volynvodproekt Institute, the Ecology Department of the Volyn Regional State Administration, the Volyn Statistics Department, the Hydrometeorological Institute, the Volyn Hydrogeological and Land Reclamation Party Laboratory, ecological passports of rivers, monographs, articles, and online publications. We also used desk analysis of archival data, literary sources, and research (field and laboratory). The research process involved a comprehensive approach combining elements of hydroecological analysis, cartography, bioindication, and critical review of scientific sources.

The following methods were used to conduct objective and thorough research:

- analysis of scientific and statistical sources, including reports from the Ukrainian Water

Resources Agency, regional water monitoring results, and scientific publications;

- comparative and analytical method - to compare data on the state of rivers in Volyn with other regions of Ukraine and Europe; Geoinformation analysis (GIS) for visualizing changes in river systems and identifying areas with an increased risk of degradation.

- expert assessment method - for analyzing the effectiveness of environmental protection measures and regional policy in the field of water resources protection;

- ecological interpretation method - for assessing water ecosystems based on indicators of pollution, regulation, landscape change, and biodiversity. These methods enabled an interdisciplinary approach to the study of Volyn rivers and provided a sound basis for substantiating the necessary measures for their protection.

Presentation of the main material. The territory of the Volyn region is characterized by a variety of natural conditions, which are mainly determined by the heterogeneity of the geological and geomorphological structure of the territory and the peculiarities of the climate, which in turn affect the distribution of surface waters, the nature of soils, and the flora and fauna. All these components of nature are closely connected and create certain natural complexes that form river waters. The hydrological regime of Volyn's rivers is shaped by a temperate continental climate and characteristic seasonal unevenness of flow [18]. The majority of annual runoff occurs in the spring (March–April), when intense snowmelt causes high water levels and periodic floods, accounting for 60–70% of the annual runoff volume. During the summer months, rivers experience low water levels due to high evaporation and low precipitation. Autumn is marked by slight increases in water levels, while in winter the rivers are covered with ice and show consistently low water levels. Due to the flat terrain and low incline (less than 2 m/km), the rivers flow slowly, with wide floodplains and a tendency to become swampy. In the context of climate change (decreased snow cover, frequent summer droughts), there is a general trend toward a decrease in runoff and a shift in its peaks. Regulating runoff using reservoirs and canals, particularly within agricultural landscapes, further alters the natural hydrological cycle. The region's water resources include 137 rivers, 269 lakes, and 11 reservoirs, Table 1 (Fig. 1).

According to statistics from the Regional Water Resources Office in Volyn Oblast, as of October 1, 2025, there are 1,085 ponds in Volyn region. According to the existing administrative-

Table 1

Reservoirs of Volyn Oblast [28]

№	Name of water reservoirs, inhabited area, district	Rivers' names	Drainage basin area, km²	Mirror area, hectares	Volume of reservoirs at NWR, million m³	
					full	useful
Water reservoirs in the Pripyat River basin						
1.	Bykhivske, Bykhiv village, Kamin-Kashyrsky district	bas. Pripyat River	35,7	78	1,54	1,46
2.	Hryvenske, Lyshnivka village, Kamin-Kashyrsky district	bas. r. Stokhid	30,9	48	1,45	1,25
3.	Kovelske, Kovel village	r. Turiya	1480,0	54	1,27	0,45
4.	Krymnovskoye, Krymno village, Kamen-Kashirsky district	bas. Pripyat River Channel Zalyudsky	21,7	56,4	1,20	0,62
5.	Krychevychi, Krychevychi village, Kovel district	bas. r.Pripyat Krichevitsa o/s	22,3	51	2,04	1,29
6.	Staromosirsk, village of Staryi Mosir, Kovel district	bas. Pripyat River Stokhid River	34,6	78	1,51	1,51
7.	Tsyrske, village of Vyderta, Kamin-Kashyrsky district	bas. Pripyat River, Tsir River	22	62	1,68	1,67
8.	Shepelsk, village of Shepel, Lutsk district	bas. r. Serna	137,0	88,0	1,55	1,55
9.	Maryanivske Maryanivka village, Lutsk district	Lipa River	36,0	118,5	1,30	1,30
	Total for the basin:		1820,2	633,9	13,54	11,10
Water reservoirs in the Western Bug River						
1.	Korteliske, Kortelisy village, Kovel district	Lake Lyubovel	41,0	180,0	4,2	3,45
2.	Tursk,Tur village, Kovel district	Zabolotivsky Channel	163	1357,3	21,5	21,5
	Total for the basin:		204,0	1537,3	25,7	24,95
	Total for the region:		2024,2	2171,2	39,24	36,05

Table 2

Amount of rates by administrative Districts of Volyn region on October 1, 2025 [28]

Name of the administrative-territorial district	River basin	Quantity, units
Volodymyr-Volynskyi	Pripyat	43
	Western Bug	271
Kamin-Kashirsky	Pripyat	135
	Western Bug	-
Kovel	Pripyat	94
	Western Bug	47
Lutsk	Pripyat	488
	Western Bug	7
Total		**1085**
including	Pripyat	760
	Western Bug	325

territorial division, the largest number of ponds is recorded in Lutsk (495), Volodymyr-Volynskyi (314), Kamin-Kashyrskyi (128), and Kovel (141) districts. The summary of the main parameters of ponds by administrative districts and river basins is presented in Table 2 [28].

The hydrographic network of the Volyn region belongs to the basins of the Pripyat and Western Bug rivers, but most of the rivers belong to the Pripyat. The main rivers often originate outside the region, with only a few (Turiya, Stokhid, Vyzhivka) flowing entirely through the territory of Volyn. The Pripyat River and its tributaries, the Styr, Turia, and Stokhid, are the largest rivers in the Dnieper basin in the region. The Western Bug flows along the western border with its tributary Luga and 24 rivers, which flow mainly from south to north with a slow current through the gentle terrain. Most rivers are shallow and not navigable. River network density is 0.25–0.47 km/km² for the Pripyat River and 0.22–0.35 km/km² for the Western Bug River. Rivers are used for recreation, tourism, swimming, and fishing [18].

The rivers of the region have a flat regime with predominantly snow feed, although in recent years there has been a shift towards rain feed, which determines their level and runoff regimes. They are characterised by high spring floods and low low water levels, sometimes disrupted by summer and winter floods. The drainage regime is formed under the influence of physical and geographical factors - geology, relief and climate, which affect the distribution of drainage and the water content of rivers.

Hydrogeological conditions significantly influence the formation of low-water flow, which is related to the groundwater regime and erosion. The flow of rivers in the region is uneven throughout the year and varies depending on the water content of the year. Maximum flows

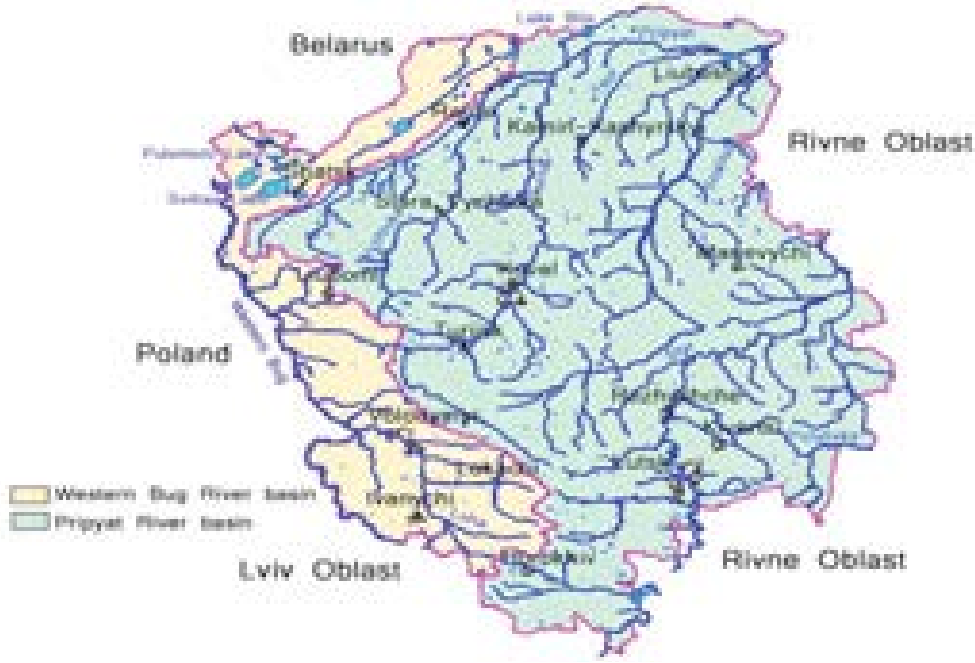


Fig. 1. Hydrological network of Volyn

are observed during spring floods and summer-autumn floods.

Most small watercourses are polluted by industrial, agricultural and municipal wastewater. Due to the reduction in the transport capacity of the river flow, they become silted up. The water regime of small watercourses is particularly sensitive to the reduction in groundwater levels during land reclamation and groundwater extraction [9].

The low technological culture of fertiliser use in agriculture worsens the water-physical properties of soils, affects the formation of runoff and sediments, and contributes to the eutrophication of watercourses. Many small river systems have dried up.

The solid runoff of Volyn rivers reflects the erosive activity of surface waters, especially in the upper reaches of the Pripyat tributaries on the elevations of the Volyn Upland. In the Volyn Polissya, the karst territory with sandy-clay deposits has weak water erosion and low runoff of mineral sediments. The solid runoff causes variable water turbidity, ranging from 3-5 g/m^3 (Turiya) to 12-60 g/m^3 (Styr), especially during torrential floods [18].

The thermal regime of the region's rivers depends on the air temperature, but this dependence is disrupted due to regulation (reservoirs, ponds) and the influence of groundwater with a different temperature. When the air temperature drops below zero, ice formations form on the rivers, and the ice period lasts 3–4 months. The ice cover is unstable, the rivers thaw and freeze several times, and complete clearing of ice occurs 5–10 days after thawing.

Focus on the study of the main rivers of the Volhyn region.

The Western Bug - is a river in Ukraine, Belarus and Poland, a right tributary of the Vistula. It is the only river in Ukraine that flows into the Baltic Sea. It originates in the northern edge of Podillia, flows through Volhynia from south to north and further serves as the state border with Poland. The river flows through Ukraine to the city of Ustyluh, and then along the border. The floodplain is narrow (up to 1 km), and the riverbed is winding. The river is 10 to 100 m wide and 0.5–4.5 m deep. There are 80 lakes in the Western Bug river basin in Volhynia, including the Shatsk Lakes (39 lakes), the largest of which is Lake Svitiaz. A number of reservoirs have been built on the river. The river is navigable in its lower reaches [7]. The Western Bug is a natural border between Ukraine and Poland, which makes it very important for international water relations [29]. This fact is important for studying international water management and environmental standards between countries. The Western Bug is crucial to the ecosystem of the Vistula basin, influencing the hydrological regime of Poland's rivers, particularly those flowing into the Baltic Sea. The river basin of the Western Bug is classified as class 5 in terms of water pollution, which indicates severe pollution [5;31]. The river basin covers an area of 3,102.08 km², which is 15.3% of the region's area. The main polluters are wastewater from the city of Volodymyr and surrounding settlements, as well as runoff from agricultural land. Thanks to its natural conditions, the Western Bug is a biosphere reserve for numerous species of plants and animals, including rare species of animals, in particular rare species of fish (ide, trout, grayling, dace, gudgeon, river minnow), as well as otters and beavers, which are important for maintaining the region's biodiversity [13].

The Luga is a right tributary of the Western Bug, whose source is located on the Gorokhiv Upland and flows into the Western Bug near the town of Ustyluh. The river is 93 km long, and its basin covers an area of 1,348 km². It is fed by groundwater and precipitation. It flows through the Lokachi, Ivanychi, and Volodymyr communities. It has several tributaries and over 20 ponds. Due to anthropogenic influence (land reclamation, dams, channel straightening), the hydrological regime has been altered, the flow has been reduced, and the sources have been silted up [18].

The Pripyat is the largest tributary of the Dnieper in terms of basin area, length, and water content, flowing through the Volyn, Rivne, and Kyiv regions of Ukraine and Belarus. It is considered one of the oldest rivers in Europe, formed after the last ice age [11]. After the Chernobyl accident in 1986, part of the river flowed into the exclusion zone, turning it into a natural laboratory for studying the restoration of ecosystems after radioactive contamination. Research has shown that the flora and fauna on the banks of the Pripyat are gradually recovering, despite radioactive contamination. The Pripyat River is one of the largest rivers without natural reservoirs, which helps to preserve its natural regime, although some artificial structures are used to regulate floods. The Pripyat River basin (upper reaches to the town of Ratne) and the Vyzhivka River are classified as Class 1 in terms of water pollution, which indicates their high quality. They cover an area of 3,153.28 km², which is 15.61% of the region's area. Pollution in these basins is minimal, and the water is characterized as "clean." The Pripyat River mainly flows through the Polissya lowlands among marshy banks. Its valley is weakly pronounced in the upper reaches and more distinct in the lower reaches, with a width of 5–8 km. The floodplain stretches along the entire course, with two terraces above the floodplain [18]. The upper reaches of the river are canalized, while further downstream it is

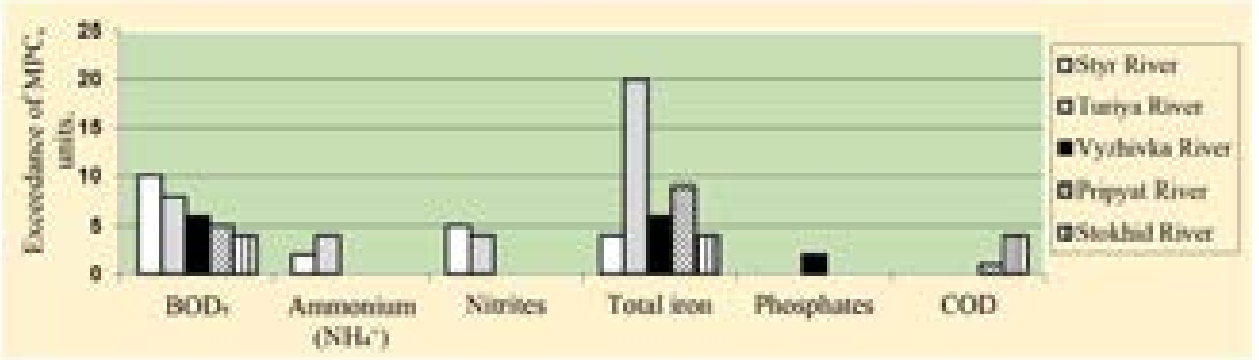


Fig. 2. Pollutants in the Pripyat River basin [11]

winding, with meanders, oxbow lakes, channels (in particular to Lake Nobel) and sandy islands. It has a mixed water supply, mainly from snowmelt. Its regime is characterized by prolonged flooding in the spring. The Pripyat freezes only in mid-December. The swamps in its basin affect the color of the water. Most of its tributaries are canalized; among the right-bank tributaries are the Turia, Stokhid, Styr, and Horyn. Monitoring since the 2000s has recorded pollution of the waters with organic and biogenic substances. The basin is experiencing eutrophication due to excess nitrogen and phosphorus, mainly from point sources. The most polluted rivers are the Horyn, Styr, and Turia, the latter due to effluents from enterprises in Kovel. In the Pripyat River, water quality varies: in general, the water is "clean" in terms of salt composition, but "moderately polluted" with toxic substances.

In 2019–2024, Pripyat remained contaminated: exceedances of MPCs for ammonium nitrogen, iron, chromium, and copper were stable, with peak values up to 10 MPCs (Fig. 2) [11]. At the same time, in terms of salt composition, the water remained "very clean," and in terms of other indicators, "fairly clean" or "slightly polluted," which corresponds to quality class II. According to I.M. Netrobchuk (2017–2023), the quality of water in Pripyat in the Volyn region is declining due to effluents from municipal enterprises, villages without centralized sewage systems, and farming [9]. In the Chernobyl exclusion zone, the river has elevated toxic and radioactive contamination, which negatively affects its ecological condition (Fig. 3) [9].

The Stokhid is a right tributary of the Pripyat, 188 km long, with a basin of 3,125 km². It originates near the village of Semerynske (Volodymyr district). The upper reaches of the valley are distinct (up to 4.5 km wide), while further downstream the width ranges from 7 to 10 km. Below the village of Zayachivka, the river forms numerous branches. It is fed by precipitation, surface water, and groundwater. The Stokhid receives runoff from drainage systems and is connected to Lake Chervyshche by a canal. The riverbed is deepened and straightened for 50 km.

Near the village of Lyubeshiv, most chemical indicators of water are normal, but ammonium ions and COD exceed the norm, there are signs of organic pollution, without significant toxic or radioactive problems [18].

The Turiya is a right tributary of the Pripyat River, 184 km long. It originates in a swamp near the village of Zaturtsi and flows through the Polissya lowlands through several communities in Volhynia. The floodplain is bilateral, sometimes swampy, with oxbow lakes and lakes [18]. The river has a pronounced spring flood. The basin is forested, partially reclaimed (≈20%), and there is a reservoir in Kovel.

The Turia flows through one of the largest wetlands in Western Ukraine. These wetlands within the Turia basin are critically important to

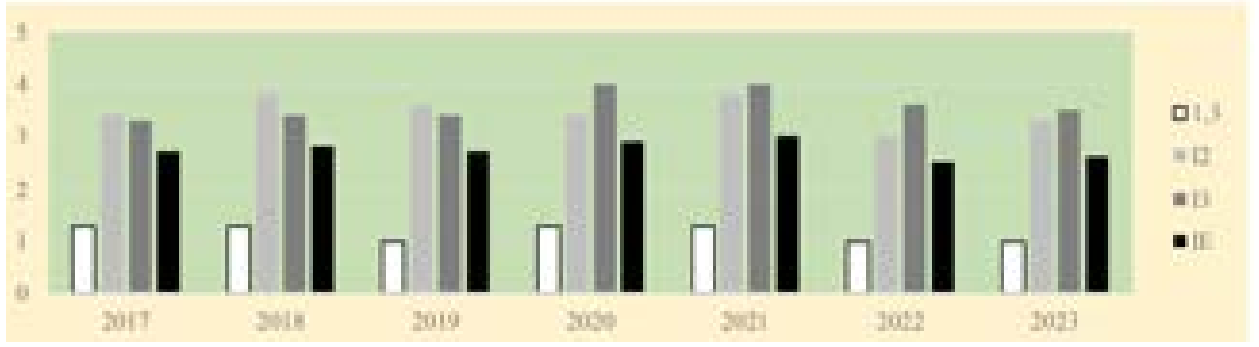


Fig. 3. Block and ecological indices of water quality in the Pripyat River (Richytsia village) (salinity index - I_1, saprobity index - I_2, toxic substances index - I_3, quality index- I_E)

the ecosystem as they help preserve biodiversity and stabilize the water regime. The Turia River was an important waterway in the Middle Ages, particularly for transporting goods between the Volhynian and Galician principalities. It was part of a larger system of waterways connecting the Dnieper and the Baltic Sea. There are natural mineral water springs in the vicinity of the Turia River that are used for therapeutic and health purposes, particularly in the regions near the cities of Kovel and Lutsk. The city of Kovel has the greatest impact on water pollution in the Turia River due to industrial wastewater, unauthorized connections to the sewage system, landfills, and violations of water protection regulations [18]. The water quality of the Turia River is generally good: pH, nitrite nitrogen, and chlorides correspond to class 1 ("excellent" condition), while the worst water quality indicators (dissolved oxygen, BOD_5, COD, and nitrates) belong to class 3 ("satisfactory"). The worst values were recorded in July (Table 3).

The Styr is a river 494 km long, 70 km of which are in Belarus, with the rest in Ukraine (Lviv, Volyn, and Rivne regions). It originates near the town of Brody, and its basin covers 11,200 km². The valley is trapezoidal in shape and runs through the Podillia Upland and the Polissia Plain. In the upper reaches, the relief is rugged with ravines, in the middle part it is hilly, and in the lower part it is flat and marshy. The bottom is sandy, with stones, silt, and pits. Spring floods last 2–5 weeks, flooding the valley. The water is clear, and there are three reservoirs in the basin. The Styr is one of the most important rivers in Volhynia, and its flow is highly variable. It is known that in the spring, the water in the Styr River can rise to 4–5 m, causing regular floods. This makes the Styr an important object for studying hydrological changes in the context of climate change. The Styr is an example of a river with a dominant underground water supply in certain parts of its basin. This reduces the rate of water level fluctuations and allows the river to remain relatively stable even during droughts. The Styr River is undergoing negative changes in its ecosystems due to the impact of land reclamation. However, natural processes have been restored in some sections of the river, in particular through the creation of ecological corridors. The Styr River basin (outside the city of Lutsk) is classified as class 5 in terms of water pollution, which indicates severe pollution. It covers an area of 3,102.08 km², which is 15.3% of the region's area. The main sources of pollution are wastewater from the city of Lutsk and surrounding settlements, as well as agricultural runoff. The water quality of the Styr River remained stable, mostly corresponding to category 2 of class II quality ("very good," 'clean'), with the exception of 2009, 2010, and 2017, when category 3 ("good," "fairly clean") was recorded. The water quality is affected by wastewater from housing and communal services and enterprises in Mlyniv, Dubno, and Lviv region (through tributaries). The influence of the city of Lutsk is reflected in elevated calcium concentrations, Cr^{6+} and dichromate oxidizability. The Styr has stable water quality, although anthropogenic impact and pollution from wastewater sometimes reduce its ecological status [18; 11].

The Tsyr is a right tributary of the Pripyat River, flowing from a marshy area near the village of Yalovatsk in the Kamin-Kashirsky District. Its catchment area is 538 km², and the river is 52 km long. The bed of the Tsyr is straightened and serves as the main channel of the drainage

Table 3

Water quality of the Turia River within the city of Kovel according to the "Methodology for classifying surface water bodies..."[18]

Indicators	MPV quality class			
	29.05.2024 Sample №1	15.06.2024 Sample №2	11.07.2024 Sample №3	16.08.2024 Sample №4
Hydrogen index pH, units pH	7,3 excellent	7,7 excellent	7,5 excellent	7,3 excellent
Dissolved oxygen, g O_2/dm³	11,4 excellent	9,3 excellent	3,2 satisfactory	8,1 excellent
Biological oxygen consumption (BOD_5), mgO_2/dm³	2,6 excellent	2,4 excellent	5 satisfactory	2,5 excellent
Chemical oxygen demand, mgO/dm3	21,6 good	40,3 satisfactory	30 satisfactory	17,6 good
Ammonium nitrogen, mgN/dm3	0,36 good	0,18 good	0,19 good	0,21 good
Nitrate nitrogen, mgN/дdm	0,56 excellent	2,74 satisfactory	2,81 satisfactory	2,97 satisfactory
Nitrite nitrogen, mgN/dm3	0,003 excellent	>0,003 excellent	0,003 excellent	0,003 excellent

system. The catchment area occupies the Verkhniopripiatskaya accumulative lowland. The valley is indistinct, 1 to 3 km wide with barely noticeable slopes, the floodplain is swampy and peaty, and the riverbed is marked by meanders and branches. In addition, there are six karst lakes in the catchment area [7].

The Vyzhivka is a right tributary of the Pripyat River, 81 km long, with a basin area of 1,272 km². It flows through the Polissya Lowland in the Kovel District and empties into the Pripyat River near the town of Ratne. The valley is not very pronounced, and the floodplain is swampy. The river is used for land reclamation and drainage, and two ponds have been constructed. Monitoring reveals excessive BOD_5 and iron concentrations, indicating organic pollution. The ecological condition of the river, especially in its middle and lower reaches, is unsatisfactory and requires restoration [7].

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After calculating the Redfield number, it has been found that nitrogen was the limiting element for the Luga, the Vyzhivka, and the Stokhid rivers. This indicates that blue-green microalgae predominate in the waters of these rivers. In other rivers, namely the Turia and Styr, the limiting element is phosphorus, which contributes to the spread of green algae [11].

In general, it has been determined that these rivers had an average degree of purification, which is not critical for the development of eutrophication. Only in recent years of observation in the Vyzhivka River has it been found that the purification capacity has become below average (Fig. 4).

Thus, there is a noticeable tendency towards phosphorus limitation, primarily for the Turia River, accompanied by the predominance of green algae communities. The balance of elements (N and P) according to Redfield's number is observed mainly for the Styr River, which indicates the absence of active eutrophication processes in the presented series of years [20].

Thus, Redfield's calculation revealed that for the Vyzhivka, the Luga, and the Stokhid rivers, in the vast majority of years, nitrogen was the limiting factor, leading to the development of algae (blue-green) communities. For the Turia and the Styr rivers, the limiting factor is mostly phosphorus, which causes the development of green algae (protocock) communities. The rivers Styr, Stokhid, Turia, Western Bug, and Luga are characterized by a decrease in maximum flows during 1991-2020. The Vyzhivka River at both hydrological stations is characterized by an increase in maximum flow. The Pripyat River (Rychytsia hydrological station) and downstream (Lyubyaz hydrological station) has maximum flows in different directions [25].

The main environmental problems of river systems in the Volyn region are:

- the disruption of the natural hydrological regime due to large-scale drainage reclamation, which led to a decrease in groundwater levels. A reduction in the area of wetlands and floodplains, and a decrease in the base (underground) flow of rivers, which caused small rivers to dry up during the summer and autumn low water period, a sharp increase in flooding in the spring, and a decrease in the stability of river ecosystems to climatic fluctuations;

- an anthropogenic transformation of riverbeds and floodplains, i.e., straightening, deepening of riverbeds, and their canalization, which led to the

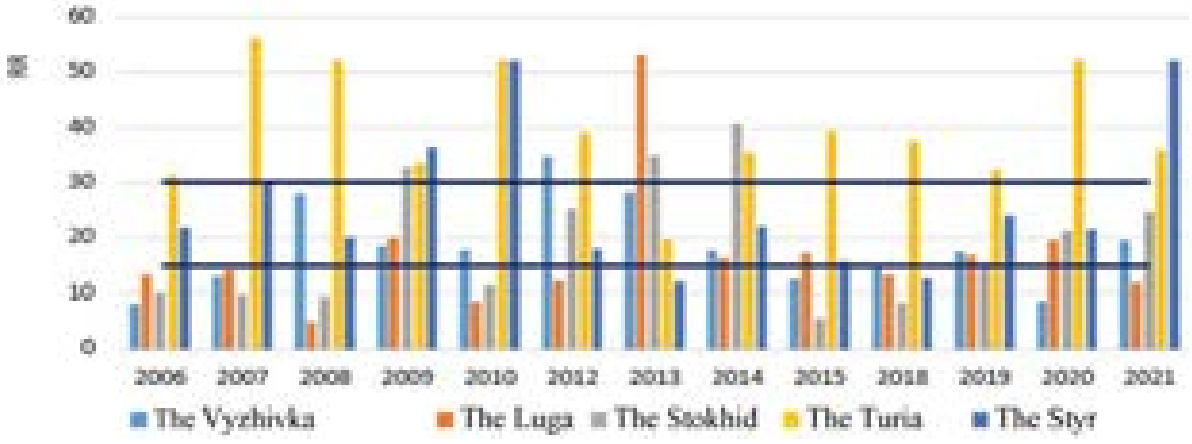


Fig. 4. Long-term average dynamics of the Redfield number in the water of rivers in the Volyn region

loss of river sinuosity, reduction of floodplain areas, disruption of the hydrological connection between the riverbed and adjacent territories, which in turn caused the degradation of channel-floodplain ecosystems, a reduction in biodiversity, and a deterioration in water self-purification processes;

- the deterioration of surface water quality due to diffuse runoff from agricultural land, domestic wastewater from settlements, drainage water from drained peatlands, which led to an increase in the content of biogenic substances, eutrophication of water bodies, and unstable oxygen conditions during the low-water period;

- the degradation of small rivers has led to limited water availability and high sensitivity to local influences, resulting in the partial or complete disappearance of individual watercourses from the region's hydrographic network.;

- the intensification of climate change, in particular, longer periods of drought, uneven precipitation, rising air temperatures, which exacerbates water shortages, ecological instability of river systems, and the risk of degradation of aquatic ecosystems.

The main ways to preserve and restore the region's river systems should be:

- the restoration of the natural hydrological regime through optimization of drainage systems, regulation of drainage channels, re-wetting of degraded peatlands, restoration of the role of wetlands as natural water reservoirs;

- the renaturalization of river channels and floodplains by restoring the sinuosity of straightened sections, expanding and preserving floodplains, and eliminating excessive engineering regulation of channels;

- the reduction of diffuse pollution through the preservation and restoration of coastal protection strips, the introduction of soil protection technologies in agriculture, and the reduction of biogenic substances entering watercourses;

- the improving wastewater treatment by modernizing treatment facilities, controlling unauthorized discharges, and conducting environmental monitoring of small settlements;

- a basin-based approach to water resource management through integrated management at the level of the Pripyat and Western Bug basins, combining environmental and water management interests, and community participation in river conservation;

- the adaptation to climate change through the development of nature-based solutions, restoration of forests, wetlands, and floodplains, and improvement of the ecological sustainability of aquatic ecosystems.

Thus, the river systems of the Volyn region are in a tense ecological state, caused by a combination of anthropogenic influences and modern climate change. The preservation and restoration of rivers is only possible with a comprehensive, basin-wide, and ecosystem-based approach that combines environmental, hydrological, and socio-economic measures.

Conclussions

Based on the research, it hass been found that:

1. The rivers of Volyn play a key role in maintaining the ecological balance of the region, providing water resources, biodiversity, and natural equilibrium.

2. The main challenges for the region's river ecosystems are related to water pollution, artificial regulation of river beds, degradation of coastal areas, and disruption of the natural hydrological regime.

3. The existing water resource management system is fragmented, with low-level environmental protection measures and insufficient coordination between authorities.

4. Environmental monitoring of rivers should be expanded to include bioindication and geoinformation methods.

5. Integrated water resource management, an ecosystem approach to riverbed restoration, and the development of legal and financial mechanisms for the protection of river systems are recommended.

6. The protection of Volyn's rivers should become a priority for regional environmental policy, with the active participation of local communities and the scientific community.

The implementation of comprehensive environmental protection measures is key to preserving these water systems as sources of life for present and future generations.

Scientifically based recommendations. Based on the analysis, a number of practical and strategic recommendations have been formulated, the implementation of which will contribute to the conservation and restoration of river ecosystems in Volyn and ensure their sustainable functioning:

1. Integrated water resources management (IWRM). It is necessary to combine environmental, economic, and social approaches to water resource use, taking into account the specific characteristics of each basin. This requires the development of water resource management plans at the river basin level in accordance with European requirements, in particular the provisions of the EU Water Framework Directive.

2. Expansion of the water monitoring system. It is advisable to introduce systematic comprehensive monitoring, including physical, chemical, biological, and hydrological parameters, with a particular focus on small watercourses that are most sensitive to external influences.

3. Renaturalization of riverbeds and restoration of riparian ecosystems. It is recommended to carry out river clearing measures only in cases of critical necessity, instead restoring the natural sinuosity of riverbeds, wetlands, coastal areas, and meadows as elements of self-regulation of the water system.

4. Limiting anthropogenic pressure and introducing environmentally safe practices. It is necessary to strengthen control over the discharge of untreated wastewater, restrict development in coastal areas, regulate agrochemical pressure near rivers, and encourage the use of nature-based measures.

5. Development of environmental education and public awareness. Effective protection of rivers is impossible without changing public attitudes towards them. It is advisable to implement educational programs and environmental awareness campaigns, and to involve young people and local communities in monitoring and nature conservation initiatives.

6. Development of legal and financial mechanisms to support environmental protection measures. It is necessary to improve the regulatory framework for water protection and ensure targeted funding for river ecosystem restoration projects from state, local, and international sources.

7. Deepening scientific research. It is advisable to initiate research programs for long-term study of Volyn's river systems using geoinformation technologies, bioindication methods, and mathematical modeling of ecosystem processes. The results obtained can serve as a basis for the formation of regional strategies, water resource management programs, and the implementation of environmental protection projects.

Внесок авторів: всі автори зробили рівний внесок у цю роботу
Конфлікт інтересів: автори повідомляють про відсутність конфлікту інтересів
Декларація про використання генеративного штучного інтелекту: Автори використовували інструменти генеративного штучного інтелекту (GenAI) для допоміжної роботи: **модель GPT-5.5 (OpenAI) під час перевірки правильності перекладу з однієї мови на іншу та під час оформлення списку використаних джерел**. Усі результати роботи з цими інструментами були ретельно контрольовані, перевірені та, за необхідності, відредаговані авторами. Автори несуть повну відповідальність за зміст та цілісність публікації.

Authors' Contributions: All authors contributed equally to this work.
Conflicts of Interest: The authors declare no conflict of interest.

Declaration of use of generative artificial intelligence: The authors utilized generative artificial intelligence (GenAI) tools in a supportive capacity: GPT-5.5 model (OpenAI) when checking the correctness of translation from one language to another and when creating a list of references. All outputs from these tools were carefully supervised, reviewed, and, where necessary, edited by the authors. The authors retain full responsibility for the content and integrity of the publication.

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ISSN 2410-7360 (Print)
ISSN 2411-3913 (Online)
Вісник Харківського національного університету імені В.Н. Каразіна Серія «Геологія. Географія. Екологія» 2026 64 С. 424–436
Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology 2026 64 424–436

Річкові системи Волинської області: стан, проблеми та шляхи збереження

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АНОТАЦІЯ

Дане дослідження спрямоване на всебічне вивчення екологічного стану річок Волинської області у сучасних умовах, визначення ключових загроз для водних екосистем та обґрунтування шляхів їх збереження і сталого використання. Виконуючи дану роботу було застосовано методи дослідження: порівняльно-географічного аналізу, математичної статистики, картографічний, польових спостережень й узагальнення, з використанням комплексних підходів (генетичного, історичного, системного, басейнового). Новизна дослідження полягає у розвитку підходів до аналізу та оцінки антропогенних змін у водозбірних територіях незначних водотоків з метою вирішення завдань з поліпшення природоохоронної ситуації в межах Поліського краю та Лісостепової зони Волинської області. У роботі подано систематизований виклад сучасного стану водозбірних територій річкових систем Волині, проведено аналіз і оцінку різновидів антропогенного впливу на маловодні водотоки регіону. Розкрита якісна та кількісна характеристики різних навантажень на басейни річок та розроблені відповідні індекси їх оцінки щодо трансформації їх природного середовища. У роботі коротко описано природно- кліматичні та фізико-географічні передумови формування річкового стоку. Оцінено екологічний стан річкових систем Волині та вплив різних галузей господарства на нього, визначено ключові чинники деградації та запропоновано заходи для зменшення забруднення і поліпшення водного середовища. Розглянуто нормативні показники якості води та шляхи охорони і подальше раціональне використання річок у народному господарстві. На основі аналізу сформульовано низку практичних та стратегічних рекомендацій, реалізація яких сприятиме збереженню і відновленню річкових екосистем Волині та забезпеченню їхнього сталого функціонування, зокрема інтегроване управління водними ресурсами (IWRM), розширення системи моніторингу води, ренатуралізація русел і відновлення прибережних екосистем, обмеження антропогенного навантаження та впровадження екологічно безпечних практик, розвиток екологічної освіти та просвіти населення.

ІНФОРМАЦІЯ ПРО СТАТТЮ :

Рукопис надійшов
23 січня 2026

Отримано після рецензування
28 квітня 2026

Затверджено до друку
25 травня 2026

Опубліковано онлайн
30 травня 2026

Ключові слова:

антропогенне навантаження; річковий стік; річковий басейн; екологічний стан; природне середовище; забруднення; стале водокористування; водні ресурси; гідроекологія; моніторинг довкілля.

https://doi.org/10.26565/2410-7360-2026-64-34

УДК: 35.075.5-027.555:502.175:504.06(477)

ГІС-моніторинг як інструмент публічного управління екологічною безпекою територіальних громад України

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АНОТАЦІЯ

У статті обґрунтовано роль геоінформаційного моніторингу як сучасного інструменту публічного управління екологічною безпекою територіальних громад України в умовах децентралізації та воєнних викликів. Актуальність дослідження зумовлена зростанням екологічних ризиків, пов'язаних із накопиченням відходів, забрудненням атмосферного повітря і водних ресурсів, деградацією ґрунтів та екологічними наслідками збройної агресії, що потребують оперативного та просторово орієнтованого управлінського реагування на місцевому рівні. Проаналізовано сучасні наукові підходи до застосування геоінформаційних систем і технологій дистанційного зондування Землі в екологічному моніторингу, зокрема дослідження, які засвідчують ефективність поєднання просторових і статистичних даних для оцінювання стану довкілля. Встановлено, що більшість наявних робіт зосереджена на технічних і методичних аспектах ГІС-моніторингу, тоді як питання інтеграції його результатів у практику публічного управління територіальних громад залишаються недостатньо розробленими. На основі офіційних статистичних даних про динаміку утворення відходів, викидів забруднюючих речовин в атмосферне повітря та забору води з природних джерел у 2018–2022 рр. показано просторову диференціацію екологічного навантаження та обмеженість традиційних підходів до екологічного контролю. Обґрунтовано доцільність використання ГІС для виявлення локальних «гарячих точок», верифікації екологічних збитків і підтримки управлінських рішень на рівні територіальних громад. Окрему увагу приділено управлінському значенню екологічних ризиків для територіальних громад з урахуванням їхніх повноважень та чинного нормативно-правового регулювання. Уточнено, що ефективне застосування ГІС-моніторингу потребує поетапного впровадження, яке включає аудит наявних даних, формування бази геоданих, вибір програмної платформи, підготовку персоналу та інтеграцію геоінформаційних інструментів у процеси публічного управління. Запропоновано модель ГІС-моніторингу екологічної безпеки територіальної громади, яка інтегрує різнорідні джерела даних, геоінформаційні інструменти та управлінський цикл «моніторинг – оцінка – планування – реалізація – контроль». Доведено, що впровадження такої моделі сприяє підвищенню ефективності екологічного управління, прозорості прийняття рішень та сталому розвитку територій.

ІНФОРМАЦІЯ ПРО СТАТТЮ :

Рукопис надійшов
9 лютого 2026

Отримано після рецензування
20 травня 2026

Затверджено до друку
25 травня 2026

Опубліковано онлайн
30 травня 2026

Ключові слова:

геоінформаційні системи; ГІС-моніторинг; екологічна безпека; територіальні громади; публічне управління; екологічний моніторинг; просторовий аналіз; сталий розвиток; екологічні ризики.

Вступ

Екологічна безпека є одним із ключових компонентів сталого розвитку територій та базовою умовою збереження здоров'я населення, природного потенціалу й ресурсної спроможності держави. Для України ця проблематика набула особливої гостроти у зв'язку з довготривалими процесами трансформації економіки, наслідками промислового навантаження, нерівномірністю територіального розвитку, а також з екологічними наслідками збройної агресії та руйнуванням об'єктів критичної інфраструктури.

У таких умовах традиційні підходи до екологічного контролю (переважно перевірки, паперова звітність, інституційна фрагментація) є недостатньо ефективними для оперативного управління ризиками. Практика країн ЄС демонструє, що актуальними інструментами публічного управ-

Як цитувати : Тюріна Діна (2026). ГІС-моніторинг як інструмент публічного управління екологічною безпекою територіальних громад України. *Вісник Харківського національного університету імені В.Н. Каразіна Серія «Геологія. Географія. Екологія»*, (64), 437–445. https://doi.org/10.26565/2410-7360-2026-64-34

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ління екологічною безпекою є цифрові рішення, системи збору й обробки даних, інтегровані моніторингові платформи, а також застосування геоінформаційних систем (ГІС) як універсального інструменту для просторового аналізу загроз і ресурсів.

Розвиток ГІС-моніторингу в Україні у межах цифровізації публічного управління, реформ децентралізації та впровадження електронних сервісів створює підґрунтя для підвищення спроможності територіальних громад у сфері управління довкіллям. Саме громади стають первинною ланкою реагування на локальні екологічні проблеми: поводження з відходами, забруднення повітря і вод, деградацію ґрунтів, підтоплення, стихійні пожежі тощо.

Аналіз останніх досліджень і публікацій. Проблематика застосування геоінформаційних систем у сфері екологічного моніторингу активно розвивається в сучасних наукових дослідженнях у контексті цифровізації аналізу довкілля, інтеграції просторових даних та використання дистанційного зондування Землі. ГІС розглядаються як базовий інструмент екологічної аналітики, що забезпечує поєднання статистичних і просторових показників для оцінювання стану природних ресурсів та антропогенного навантаження.

У фундаментальних оглядових працях з геоінформаційного аналізу та екологічного моніторингу обґрунтовано роль геоінформаційних систем як універсального інструменту екологічного аналізу, моніторингу природних процесів і візуалізації екологічних загроз [19; 20].

Сучасні дослідження, зосереджені на методичних аспектах ГІС-моніторингу. Зокрема, у працях J. Dong, X. Liang, B. Du та співавторів узагальнено сучасні методи застосування ГІС в оцінюванні екологічного впливу та окреслено перспективи розвитку інтегрованих моніторингових платформ [12]. У роботах M. Nizamani, M. Awais, M. Qayyum та ін. продемонстровано можливості поєднання ГІС і супутникових даних для аналізу екологічного стану урбанізованих територій [16].

Окремі напрями досліджень присвячені моніторингу конкретних компонентів довкілля. Так, A. Räsänen, A. Tolvanen, S. Kareksela довели ефективність використання супутникових знімків і ГІС для аналізу гідрологічних показників екосистем [17], а P. Fraternali, L. Morandini, S. L. Herrera González узагальнили сучасні підходи до виявлення та картографування відходів за допомогою методів дистанційного зондування [15].

Вагомий внесок у розвиток ГІС-моніторингу зроблено у дослідженнях, присвячених використанню геопросторових великих даних та хмарних платформ, зокрема Google Earth Engine, що дозволяють здійснювати екологічний моніторинг у масштабах великих територій та в динаміці. Нормативну основу для впровадження таких підходів у Європейському Союзі заклала Директива INSPIRE (2007/2/EC), яка визначає принципи створення інфраструктури просторових даних для моніторингу довкілля [14] .

Отже, сучасні наукові дослідження формують ґрунтовну методичну та аналітичну базу застосування ГІС у сфері екологічного моніторингу, що відкриває можливості для подальшого розвитку їх управлінського потенціалу в системі публічного управління.

Невирішені аспекти загальної проблеми. Незважаючи на значний науковий доробок, низка аспектів застосування ГІС-моніторингу залишається недостатньо розкритою саме в контексті публічного управління на рівні територіальних громад України. По-перше, недостатньо опрацьованими є механізми інтеграції результатів ГІС-моніторингу в управлінський цикл органів місцевого самоврядування з урахуванням їхніх повноважень і функцій. По-друге, невирішеним залишається питання адаптації інструментів ГІС-екологічного моніторингу до ресурсних можливостей, кадрового забезпечення та рівня цифрової спроможності територіальних громад, особливо в умовах децентралізації та воєнних викликів. По-третє, у наукових працях обмежено розглядаються питання використання ГІС для оперативного виявлення локальних «гарячих точок» забруднення, оцінювання екологічних наслідків воєнних дій та підтримки управлінських рішень у кризових умовах.

Це зумовлює потребу у формуванні прикладних моделей ГІС-моніторингу, орієнтованих саме на потреби територіальних громад і завдання забезпечення екологічної безпеки на місцевому рівні.

Мета статті – обґрунтувати роль ГІС-моніторингу як інструменту публічного управління екологічною безпекою територіальних громад України та розробити модель його практичного використання в умовах децентралізації.

Методи

Методологічну основу дослідження становить поєднання загальнонаукових і спеціальних методів, що забезпечують аналіз можливостей використання ГІС-моніторингу в системі публічного управління екологічною безпекою територіальних громад. У роботі застосовано методи аналізу та синтезу для узагальнення наукових підходів до використання геоінформаційних систем і дистанційного зондування, а також системний підхід для розгляду екологічної безпеки громади як комплексної соціо-еколого-інфраструктурної системи.

Статистичний і порівняльний методи використано для оцінювання динаміки ключових показ-

Таблиця 1

Утворення відходів в Україні: тенденції та управлінське значення для територіальних громад
Waste Generation in Ukraine: Trends and Governance Implications for Territorial Communities

Показник	Тенденція	Управлінське значення для громади	Повноваження громад	Нормативно-правова основа
Загальні обсяги утворення відходів	Домінування промислових відходів; високі накопичені обсяги	Потреба у плануванні системи управління відходами та зниженні екологічного навантаження	Участь у розробленні місцевих програм управління відходами, визначення пріоритетів екологічної політики громади	Закон України «Про управління відходами» [6]; Національна стратегія управління відходами в Україні до 2030 року [9]
Поводження з побутовими відходами	Залежність громад від полігонів; недостатній рівень сортування	Необхідність організації ефективного збору, перевезення, сортування та оброблення побутових відходів	Організація надання послуг з управління побутовими відходами, визначення виконавців послуг, інформаційна робота з населенням	Закон України «Про управління відходами» [6]; Закон України «Про житлово-комунальні послуги» [5]
Стан полігонів	Частина полігонів перевантажена, потребує модернізації або рекультивації	Ризики забруднення ґрунтів, водних ресурсів та погіршення санітарно-епідемічної ситуації	Контроль за належним функціонуванням місць видалення відходів, ініціювання рекультивації, участь у плануванні нової інфраструктури	Закон України «Про управління відходами» [6]; екологічні та будівельні норми щодо експлуатації полігонів
Рівень перероблення	Низький у порівнянні з практиками ЄС	Потреба у переході від захоронення до повторного використання, перероблення та циркулярної економіки	Сприяння створенню інфраструктури сортування й перероблення, залучення інвесторів і грантових ресурсів	Національний план управління відходами [7]; європейські підходи до циркулярної економіки

ників екологічного навантаження за офіційними даними Державної служби статистики України та Державного агентства водних ресурсів України. Ключову роль у дослідженні відіграють геоінформаційні методи – просторовий аналіз, картографування та візуалізація екологічних ризиків, а також узагальнення і концептуальне моделювання, що дало змогу сформувати модель ГІС-моніторингу екологічної безпеки територіальної громади та обґрунтувати її місце в управлінському циклі.

Викладення основного матеріалу. Сучасні виклики екологічної безпеки територіальних громад України мають комплексний характер і включають техногенне навантаження, накопичення відходів, погіршення якості повітря та вод, деградацію ґрунтів, а також екологічні наслідки війни.

Одним із базових напрямів оцінки екологічної безпеки є показники утворення та поводження з відходами, що безпосередньо впливають на стан земель, водних ресурсів та санітарно-епідеміологічну ситуацію в громадах. Проблема відходів має не лише екологічний, а й управлінський вимір, оскільки саме на рівні територіальних громад здійснюється організація збору, перевезення, сортування, оброблення та видалення побутових відходів, а також планування відповідної інфраструктури.

Для ілюстрації сучасного стану та основних проблем у сфері утворення й поводження з відходами в Україні, а також їхнього управлінського значення для територіальних громад, у таблиці 1 наведено узагальнену характеристику ключових тенденцій з урахуванням повноважень громад і нормативно-правового регулювання.

Аналіз наведених у таблиці 1 положень свідчить, що сфера утворення та поводження з відходами формує один із найбільш системних екологічних ризиків для територіальних громад. Високі обсяги накопичення відходів, недостатній рівень сортування, перевантаженість полігонів і низький рівень перероблення зумовлюють потребу в удосконаленні місцевого екологічного управління.

Водночас реалізація повноважень територіальних громад у цій сфері потребує належного інформаційно-аналітичного забезпечення. Ефективне планування маршрутів збору, визначення проблемних зон, моніторинг стану полігонів, виявлення стихійних звалищ та оцінювання потреб у новій інфраструктурі неможливі без використання просторово деталізованих даних.

Отже, управління відходами є важливим напрямом забезпечення екологічної безпеки громад і потребує поєднання кількісного аналізу з просторовою оцінкою. Саме тому застосування ГІС-моніторингу дає змогу підвищити обґрунтованість управлінських рішень, забезпечити візуалізацію екологічних ризиків і визначити пріоритетні напрями реагування на місцевому рівні.

Для обґрунтування необхідності впровадження ГІС-моніторингу як інструменту публічного управління екологічною безпекою територіальних громад доцільно проаналізувати динаміку ключових показників екологічного навантаження: утворення відходів, викиди забруднюючих речовин в атмосферне повітря та забір води з природних джерел (рис. 1).

Дані рис. 1 свідчать, що у 2018–2021 рр. обсяги утворення відходів в Україні залишалися

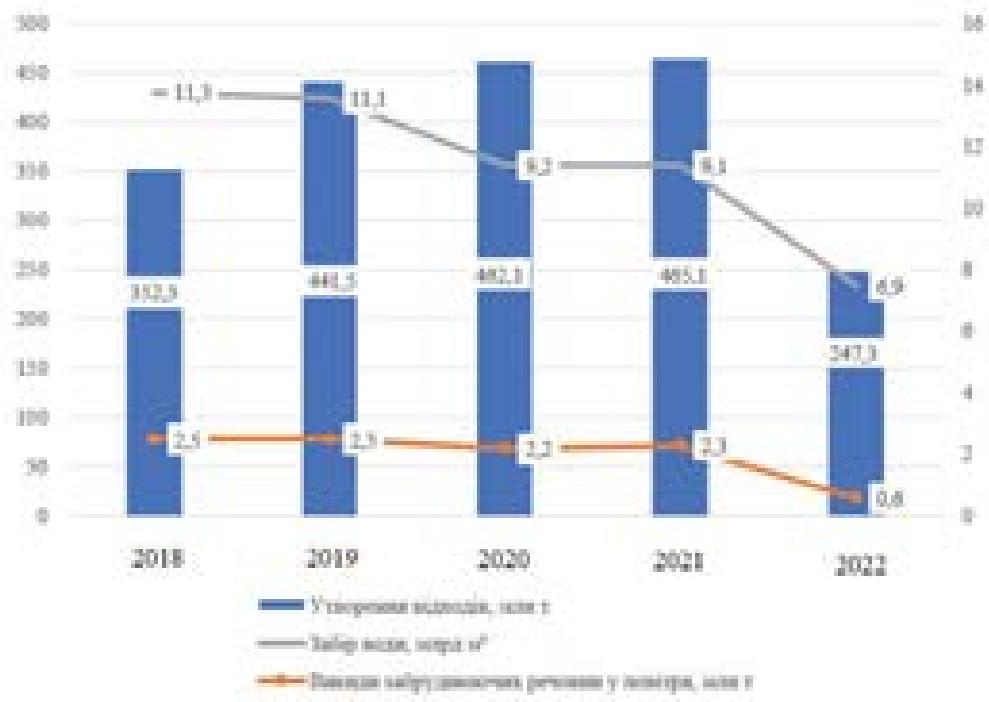


Рис. 1. Динаміка ключових екологічних показників в Україні (2018–2022 рр.) /
Примітка: дані за 2022 рік наведено без урахування тимчасово окупованих територій та територій, де ведуться активні бойові дії.
Джерело: сформовано автором за даними [1; 2; 3; 4]
Fig. 1. Dynamics of Key Environmental Indicators in Ukraine (2018–2022)
Note: The data for 2022 are presented excluding the temporarily occupied territories and territories where active hostilities are taking place.
Source: Compiled by the author based on data from [1; 2; 3; 4].

стабільно високими – від 352,3 млн т у 2018 р. до 465,1 млн т у 2021 рр., що відображає значний рівень антропогенного навантаження, зосередженого переважно у промислово розвинених регіонах. Зниження показника до 247,3 млн т у 2022 р. (без урахування тимчасово окупованих територій та зон активних бойових дій) зумовлене насамперед зниженням економічної активності та руйнуванням виробничої інфраструктури внаслідок воєнних дій, а не результатами цілеспрямованої екологічної політики.

Динаміка викидів забруднюючих речовин в атмосферне повітря демонструє формальне зменшення з 2,5 млн т у 2018 р. до значно нижчих значень у 2022 р., однак така тенденція має агрегований характер і не відображає просторового розподілу забруднення та локальних осередків підвищеного екологічного ризику в окремих територіальних громадах. Аналогічно, обсяги забору води з природних джерел скоротилися з 11,3 млрд м³ у 2018 р. до 6,9 млрд м³ у 2022 р., що свідчить про структурні зміни у водокористуванні та водогосподарські виклики на місцевому рівні.

Виявлені статистичні асиметрії та обмеження традиційних методів обліку, особливо в умовах воєнного періоду, підкреслюють необхідність використання геоінформаційних систем як інструменту просторово деталізованого моніторингу, верифікації екологічних збитків та підтримки управлінських рішень у сфері екологічної безпеки територіальних громад.

Загалом аналіз підтверджує, що екологічні ризики мають просторово диференційований характер і не можуть бути адекватно оцінені лише на основі загальнонаціональної статистики. Це обґрунтовує доцільність впровадження ГІС-моніторингу як інструменту публічного управління, що забезпечує поєднання кількісних показників із просторовим аналізом екологічних загроз на рівні територіальних громад.

Таким чином, екологічні виклики, з якими стикаються територіальні громади, носять багатовимірний характер і потребують диференційованих управлінських рішень. Узагальнення ключових екологічних ризиків та управлінських потреб представлено в таблиці 2.

Отже, екологічні ризики територіальних громад характеризуються просторовою диференціацією та обумовлюють необхідність поєднання інструментів екологічного аналізу з механізмами публічного управління, визначеними нормативно-правовою базою. Це зумовлює потребу у застосуванні цифрових геоінформаційних інструментів, які забезпечують візуалізацію загроз, інтеграцію даних та підтримку управлінських рішень на місцевому рівні.

Реформа децентралізації посилила відповідальність громад за місцевий розвиток, управління ресурсами та забезпечення безпечного середовища. Громади дедалі частіше стають: центрами екологічного планування (програми, проєкти, фінансування); суб'єктами взаємодії з

Таблиця 2

Ключові екологічні ризики громад України та управлінські наслідки
Key Environmental Risks for Ukrainian Communities and Their Management Implications

Екологічний ризик	Прояв на рівні громад	Управлінська потреба	Повноваження територіальних громад
забруднення атмосферного повітря	погіршення здоров'я населення, скарги	оперативний моніторинг, карти забруднення	Участь у контролі за дотриманням екологічних норм, інформування населення, розроблення місцевих екологічних програм
забруднення водних об'єктів	погіршення якості питної води	контроль скидів, реагування	Контроль за станом водних об'єктів місцевого значення, організація водопостачання та водовідведення
побутові відходи	нелегальні звалища, перевантажені полігони	логістика, контроль, планування	Організація системи управління побутовими відходами, визначення операторів, контроль за місцями видалення відходів
деградація ґрунтів	зниження продуктивності земель	просторовий контроль і оцінка	Контроль за використанням земель, участь у плануванні територій
підтоплення/повені	шкода інфраструктурі	прогнозування, зонування	Планування територій, заходи цивільного захисту, управління інженерною інфраструктурою
екологічні наслідки війни	руйнування, забруднення	кризовий моніторинг, фіксація	Участь у ліквідації наслідків, фіксація шкоди, взаємодія з державними органами

Джерело: сформовано автором / *Source:* Compiled by the author

бізнесом щодо екологічних стандартів; координаторами інфраструктурних проєктів (водопостачання, сміття, очищення); учасниками міжнародних грантових програм (еко-інновації, стійкість, енергоефективність).

Однак реальна спроможність громад обмежується: фрагментарністю даних; дефіцитом кадрів із цифровими компетентностями; слабкими механізмами прогнозування; недостатньою інтеграцією екологічних даних у процес прийняття рішень.

Узагальнення результатів досліджень вітчизняних і зарубіжних учених, а також матеріалів міжнародних організацій дає змогу стверджувати, що геоінформаційний моніторинг доцільно розглядати як складову механізму публічного управління, яка забезпечує комплексну підтримку управлінських рішень у сфері екологічної безпеки територіальних громад. Його функціонування ґрунтується на інтеграції процесів збору, обробки та аналізу просторово орієнтованої інформації, що дозволяє органам місцевого самоврядування формувати науково обґрунтовану та доказову політику у сфері охорони довкілля.

На початковому етапі ГІС-моніторинг забезпечує систематичний збір і накопичення даних, зокрема інформації з пунктів екологічного спостереження, галузевих і муніципальних реєстрів, статистичних показників та результатів дистанційного зондування. Агрегація таких даних у єдиному інформаційному середовищі створює передумови для подальшого їх комплексного аналізу. Наступним етапом є просторовий аналіз, що передбачає картографування екологічних ризиків, виявлення зон підвищеного навантаження, просторове зонування територій та встановлення взаємозв'язків між екологічними, соціальними й інфраструктурними чинниками.

Важливою функцією ГІС-моніторингу є прогнозування, яке реалізується шляхом моделювання можливих сценаріїв розвитку екологічної ситуації з урахуванням різних управлінських рішень або зовнішніх впливів. Це дозволяє органам публічної влади завчасно оцінювати потенційні наслідки техногенних навантажень, змін у землекористуванні або надзвичайних ситуацій. Отримані аналітичні та прогностичні результати слугують основою для прийняття управлінських рішень, зокрема під час планування природоохоронних заходів, визначення пріоритетів фінансування, розроблення програм місцевого розвитку та стратегій екологічної безпеки.

Завершальним елементом механізму є контроль і оцінювання ефективності управлінських дій, що здійснюється шляхом порівняння індикаторів стану довкілля до і після реалізації відповідних заходів. Такий підхід дозволяє не лише оцінити результативність прийнятих рішень, а й своєчасно коригувати управлінську політику.

Використання ГІС у діяльності територіальних громад забезпечує низку управлінських переваг, серед яких ключовими є наочна візуалізація екологічних проблем у межах громади, можливість оперативного виявлення так званих «гарячих точок» (нелегальні звалища, осередки забруднення повітря чи води), підвищення прозорості управління та залучення громадян до процесів прийняття рішень. Крім того, ГІС-моніторинг спрощує підготовку звітності та управлінську комунікацію між різними рівня-

ми влади, а також слугує ефективним інструментом підтримки рішень у сфері просторового планування та сталого розвитку територій.

Отже, аналіз вітчизняних і зарубіжних підходів до використання геоінформаційного моніторингу в системі публічного управління засвідчує його багатофункціональний характер та значний потенціал практичного застосування на рівні територіальних громад. Разом із тим ефективна реалізація можливостей ГІС потребує їх цілісної інтеграції в управлінський процес, що передбачає чітке визначення джерел даних, інструментів аналізу, логіки управлінського циклу та системи результативних показників.

З огляду на це виникає потреба у формуванні комплексної моделі ГІС-моніторингу екологічної безпеки громади, адаптованої до повноважень органів місцевого самоврядування, наявної інформаційної інфраструктури та специфіки екологічних ризиків конкретної території. Така модель має забезпечувати поєднання аналітичних можливостей геоінформаційних технологій із практичними завданнями муніципального екологічного менеджменту та підтримувати ухвалення обґрунтованих управлінських рішень.

У цьому контексті пропонується модель ГІС-моніторингу екологічної безпеки територіальної громади, реалізація якої передбачає створення локальної геоінформаційної платформи як інструменту інтеграції даних, аналізу екологічних ризиків та забезпечення ефективного управлінського циклу на місцевому рівні (рис. 2).

Запропонована модель відображає інтеграцію геоінформаційного моніторингу в систему публічного управління екологічною безпекою територіальної громади та демонструє логіку взаємодії між джерелами даних, геоінформаційним інструментарієм і управлінським циклом. Її реалізація передбачає створення локальної геоінформаційної платформи, яка забезпечує акумулювання різнорідної просторово орієнтованої інформації, її аналітичну обробку та трансформацію в управлінські рішення.

Практична реалізація моделі передбачає поетапне впровадження геоінформаційної системи на рівні територіальної громади. На початковому етапі здійснюється аудит наявних даних, зокрема статистичної інформації, даних екологічного моніторингу, матеріалів містобудівної документації та відкритих державних реєстрів. Наступним етапом є формування інтегрованої бази геоданих, що поєднує різнорідні інформаційні ресурси у єдиному геоінформаційному середовищі. Важливим елементом є вибір програмної платформи (зокрема, QGIS, ArcGIS або інших відкритих рішень), що забезпечує можливості просторового аналізу та візуалізації. Подальше впровадження передбачає підготовку персоналу органів місцевого самоврядування та формування відповідних цифрових компетентностей. Завершальним етапом є інтеграція ГІС у процеси публічного управління, зокрема в систему планування, моніторингу та оцінювання ефективності екологічної політики громади.

Функціонування моделі ґрунтується на використанні різних типів даних, що забезпечу-



Рис. 2. Модель ГІС-моніторингу екологічної безпеки територіальної громади
Джерело: авторська розробка
Fig. 2. GIS-Based Environmental Safety Monitoring Model for a Territorial Community
Source: Developed by the author

ють комплексність аналізу екологічних ризиків. Доцільно виокремити екологічні дані (показники викидів, стан водних ресурсів, рівень забруднення), соціальні дані (звернення громадян, скарги, результати громадського моніторингу), просторові дані (картографічні матеріали, межі територій, об'єкти інфраструктури) та супутникові дані дистанційного зондування Землі. Інтеграція цих даних дозволяє забезпечити більш точну ідентифікацію проблемних зон, виявлення «гарячих точок» та формування обґрунтованих управлінських рішень.

Модель орієнтована на підтримку повного управлінського циклу – від моніторингу та оцінювання екологічного стану до планування, реалізації та контролю природоохоронних заходів. Використання системи ключових індикаторів дозволяє здійснювати оцінку результативності управлінських дій, своєчасно виявляти проблемні зони та коригувати політику екологічної безпеки з урахуванням просторових особливостей громади.

Висновки

Виходячи з вищезазначеного**,** можна стверджувати, що екологічна безпека територіальних громад України формується під впливом сукупності взаємопов'язаних ризиків, серед яких ключовими є накопичення відходів, забруднення атмосферного повітря і водних ресурсів, деградація ґрунтів, а також екологічні наслідки збройної агресії, що суттєво ускладнюють управління довкіллям на місцевому рівні.

Встановлено, що сучасні екологічні виклики мають виражений просторово диференційований характер, що обмежує можливості їх ефективного виявлення та реагування за допомогою традиційних статистичних інструментів і зумовлює потребу у застосуванні цифрових технологій просторового аналізу.

Обґрунтовано, що геоінформаційний моніторинг виступає дієвим інструментом публічного управління екологічною безпекою, оскільки забезпечує інтеграцію різнорідних даних, наочну візуалізацію екологічних ризиків та інформаційно-аналітичну підтримку процесу ухвалення управлінських рішень органами місцевого самоврядування.

Запропонована модель ГІС-моніторингу екологічної безпеки територіальної громади може бути використана як практичний інструмент підвищення результативності екологічного контролю, планування природоохоронних заходів і моніторингу їх виконання з урахуванням територіальної специфіки.

Водночас дослідження має певні обмеження. Зокрема, використання агрегованих статистичних даних не дозволяє повною мірою врахувати локальні особливості екологічних процесів на рівні окремих територіальних громад. Також слід враховувати обмежену доступність актуальних геопросторових даних, нерівномірність їх оновлення та різний рівень цифрової спроможності органів місцевого самоврядування.

Подальші дослідження доцільно спрямувати на деталізацію показників ГІС-моніторингу для різних типів територіальних громад, розроблення прикладних геоінформаційних платформ для підтримки управлінських рішень, а також інтеграцію ГІС із системами електронного врядування та відкритих даних. Перспективним напрямом є використання технологій великих даних і штучного інтелекту для підвищення точності прогнозування екологічних ризиків і автоматизації процесів моніторингу.

Конфлікт інтересів: автор повідомляє про відсутність конфлікту інтересів

Декларація про використання генеративного штучного інтелекту: Автор використовує інструменти генеративного штучного інтелекту (GenAI) для допоміжної роботи: **модель GPT-5.5 (OpenAI) для мовного редагування**. Усі результати роботи з цими інструментами були ретельно контрольовані, перевірені та, за необхідності, відредаговані автором. Автор несе повну відповідальність за зміст та цілісність публікації.

Conflict of Interest: The author declares no conflict of interest.

Declaration of use of generative artificial intelligence: The author utilized generative artificial intelligence (GenAI) tools in a supportive capacity: GPT-5.5 model (OpenAI) for language editing. All outputs from these tools were carefully supervised, reviewed, and, where necessary, edited by the author. The author retains full responsibility for the content and integrity of the publication.

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GIS Monitoring as a Tool of Public Governance for Environmental Safety of Territorial Communities in Ukraine

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ABSTRACT

Introduction. Environmental safety is a key component of sustainable territorial development and a prerequisite for preserving public health, natural resources, and state capacity. In Ukraine, environmental challenges have intensified due to industrial pressure, uneven territorial development, decentralization reforms, and full-scale armed aggression, including damage to critical infrastructure and ecosystems. Traditional environmental control, based on inspections, fragmented statistics, and institutional separation, is insufficient for timely local risk identification.

Geographic information systems (GIS) are important for spatial environmental monitoring and decision support. The purpose of this study is to substantiate GIS monitoring as an instrument of public governance for ensuring environmental safety of territorial communities in Ukraine and to identify mechanisms for its implementation under decentralization. The object of the research is public governance in environmental safety, while the subject is GIS-based monitoring tools at the community level.

Methods. The methodological framework combines general scientific and specialized methods. Analysis and synthesis were used to generalize approaches to GIS and remote sensing in environmental monitoring. A systems approach enabled consideration of environmental safety as a complex socio-ecological and infrastructural system. Statistical and comparative methods were applied to analyze waste generation, air emissions, and water abstraction using official statistical data. GIS-based methods, including spatial analysis, cartographic visualization, and conceptual modeling, were used to identify territorial differentiation of risks and develop a GIS monitoring model integrated into the public governance cycle.

Results. The analysis shows that in 2018–2022 environmental pressures in Ukraine were characterized by significant spatial heterogeneity. Although national indicators show a decline in waste generation, air emissions, and water abstraction after 2021, these changes mainly reflect reduced economic activity caused by military actions rather than environmental policy outcomes. At the local level, risks remain concentrated in specific communities, forming “hot spots” not fully captured by traditional statistics.

The study proposes a GIS monitoring model for environmental safety of territorial communities. The model integrates environmental monitoring stations, satellite observations, open government data, municipal records, and citizen reports. It also includes GIS analytical tools and a governance cycle comprising monitoring, assessment, planning, implementation, and control. This approach enables visualization of environmental risks, identification of priority zones, and support for evidence-based public decision-making.

Conclusions. The study confirms that environmental risks in territorial communities are spatially differentiated and cannot be effectively managed by conventional control instruments alone. GIS monitoring strengthens analytical capacity, transparency, and responsiveness in local environmental management. Implementation of the proposed model can improve environmental control, support strategic planning, and contribute to sustainable development of territorial communities. Further scaling of GIS-based approaches requires institutional coordination, data standardization, and development of digital competencies within local governments.

ARTICLE INFO

Manuscript received
9 February 2026

Revised manuscript received
20 May 2026

Manuscript accepted
25 May 2026

Available online
30 May 2026

Keywords:

Geographic Information Systems (GIS), GIS monitoring, Environmental safety, Territorial communities, Public governance, Environmental monitoring, Spatial analysis, Sustainable development, Environmental risks.

In cites: Tiurina Dina (2026). GIS Monitoring as a Tool of Public Governance for Environmental Safety of Territorial Communities in Ukraine. *Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology*, (64), 437–445. https://doi.org/10.26565/2410-7360-2026-64-34 [In Ukrainian]

https://doi.org/10.26565/2410-7360-2026-64-35

UDC 911.375:551.588.7:528.8

Urban Thermal Stress Dynamics in a Tropical Coastal City: Insights from Remote Sensing Analysis in Padang City, Indonesia

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ABSTRACT

Introduction. The Urban Heat Island (UHI) phenomenon has emerged as a critical global environmental challenge, significantly undermining the sustainability of urban ecosystems and the well-being of city dwellers. UHI directly impacts human thermal comfort, increases energy demands for cooling, and escalates public health risks. In tropical regions, these challenges are particularly acute due to high baseline temperatures, intense solar radiation, and rapid urbanization. In tropical coastal settings, the complexity of thermal dynamics is further heightened by unique geomorphological features and the degradation of natural buffer zones-such as mangroves and riparian vegetation-and massive land cover transformations, thereby altering the microclimatic balance. This study focuses on Padang City, a tropical coastal city in Indonesia, which has undergone intensive land-use transformation over the past decade. This rapid development has converted extensive non-vegetated areas and agricultural lands into dense residential and commercial zones, leading to the emergence of localized thermal hotspots that threaten the city's long-term ecological resilience.
Data and Method. This research utilized multitemporal Landsat 8 OLI/TIRS satellite imagery (2015–2024) to analyze the spatio-temporal dynamics of the urban environment. The analysis focused on coastal lowlands (built-up and cultivation zones), excluding upland forests to eliminate topographic thermal bias. The Normalized Difference Vegetation Index (NDVI) was employed to quantify vegetation density, while Land Surface Temperature (LST) was retrieved using the thermal infrared bands through a rigorous series of calibration steps, including top-of-atmosphere (TOA) radiance conversion and surface emissivity estimation based on land cover proportions. To evaluate thermal stress, the Urban Thermal Field Variance Index (UTFVI) was modeled, classifying ecological quality into six categories to provide a precise spatial metric for urban environmental health.
Result and Discussion. The findings indicate that the relationship between NDVI and LST in Padang City lowlands consistently exhibits a negative correlation, underscoring the role of vegetation as a key thermal regulator. However, the strength of this relationship has progressively weakened over the study period, with the coefficient of determination declining by 2024. This trend suggests a reduction in the cooling capacity of existing urban vegetation amidst the expansion of impervious surfaces. Interestingly, during the COVID-19 pandemic in 2020, average surface temperatures declined to 28.18°C due to reduced anthropogenic heat emissions. Nevertheless, UTFVI analysis reveals that extreme thermal stress classes, specifically the 'Strongest-Worst' category, continued to expand structurally, particularly in the urban core. This expansion intensified in the post-pandemic period (2022–2024), where the 'Worst' ecological zone reached its peak spatial extent. The persistence of these hotspots reinforces the argument regarding the high thermal inertia of concrete and asphalt materials. This study finds that the thermal ecological quality of Padang City is undergoing structural degradation. Future urban planning must prioritize the integration of blue-green infrastructure with surface material albedo control and optimized morphological designs to enhance the thermal resilience against the escalating pressures of climate change and urbanization.

ARTICLE INFO

Manuscript received
30 January 2026

Revised manuscript received
10 March 2026

Manuscript accepted
25 May 2026

Available online
30 May 2026

Keywords:

UHI, UTFVI, EEI, LST, Ecological Quality, NDVI, Remote Sensing, Tropical city, Coastal City, Padang City.

In cites: Fajrin, Antomi Yudi, Syah Nurhasan (2026). Urban Thermal Stress Dynamics in a Tropical Coastal City: Insights from Remote Sensing Analysis in Padang City, Indonesia. *Visnyk of V. N. Karazin Kharkiv National University, Series Geology. Geography. Ecology*, (64), 446–457. https://doi.org/10.26565/2410-7360-2026-64-35

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1. Introduction

Globally, the Urban Heat Island (UHI) phenomenon has emerged as one of the major environmental issues affecting the sustainability of urban areas. UHI is characterized by elevated surface and air temperatures that directly influence thermal comfort, public health, energy consumption, and urban ecological stability [1-4]. In tropical regions, thermal stress tends to be more intense due to high baseline temperatures, strong solar radiation, and rapid urbanization that accelerates land cover change and alters surface characteristics.

Numerous studies indicate that urban ecological degradation-marked by the reduction of vegetation cover, the expansion of impervious surfaces, and the decline of ecosystem functions-plays a significant role in intensifying UHI effects and disrupting urban microclimatic balance [5, 6]. In tropical coastal settings, these challenges become increasingly complex. Coastal geomorphological characteristics, large-scale coastal development, and the degradation of buffer ecosystems such as mangroves and riparian vegetation substantially increase the thermal vulnerability of coastal cities in Southeast Asia [7-9]. These pressures are further exacerbated by global climate change through the increasing frequency of heatwaves, rising nighttime minimum temperatures, and altered precipitation patterns [10].

Within urban climate studies, the role of vegetation in mitigating surface heat is commonly examined using the Normalized Difference Vegetation Index (NDVI), while surface temperature distribution is represented by Land Surface Temperature (LST). A negative relationship between NDVI and LST has been widely reported [11-14], highlighting the capacity of vegetation to reduce surface temperatures through shading and evapotranspiration processes. However, in urban areas dominated by built-up surfaces, this relationship often exhibits non-linear characteristics and is strongly influenced by urban spatial configuration.

Consequently, reliance on average temperature values alone is insufficient to comprehensively capture urban thermal stress. The Urban Thermal Field Variance Index (UTFVI) was developed to account for the spatial heterogeneity of thermal stress and urban ecological quality, enabling more sensitive identification of zones experiencing high levels of thermal stress [15].

In Indonesia, rapid urban development is frequently not accompanied by adequate environmental quality protection. The reduction of green open spaces, conversion of coastal land uses, and the expansion of settlements and infrastructure have intensified thermal stress in many large and medium-sized cities [16-21]. This condition is particularly relevant to Padang City, a tropical coastal city on the western coast of Sumatra that has experienced intensive built-up area growth and land-use transformation [22]. Declining vegetation cover, increasing impervious surfaces, and mounting pressure on coastal ecosystems have contributed to the emergence of UHI hotspots, particularly in coastal zones and urban activity centers [23-25].

Nevertheless, studies that integratively combine LST, NDVI, and UTFVI analyses to understand urban thermal dynamics and ecological quality in Padang City remain limited. Furthermore, the influence of changes in human activity including periods of mobility restriction during the COVID-19 pandemic on urban thermal dynamics has received little attention in the context of tropical coastal cities, particularly in Indonesia. Addressing these gaps, this study aims to analyze the spatio-temporal dynamics of surface temperature and vegetation and to evaluate the intensity of urban thermal stress using the UTFVI approach in the lowland areas of Padang City. By employing remote sensing data and geospatial analysis, the findings are expected to provide a scientific basis for climate-adaptive urban planning and UHI mitigation strategies in tropical coastal cities.

2. Materials and Methods

Study Area and Scope. The study area covers Padang City, located on the west coast of Sumatra Island, Indonesia, which serves as the main administrative and economic center of West Sumatra Province. Spatially, this area is located within the Universal Transverse Mercator (UTM) coordinate system, Zone 47S, and directly borders the Indian Ocean to the west, while its eastern part is mostly occupied by protected forest areas (Fig. 1).

Padang City exhibits highly heterogeneous topographic characteristics, with relatively flat coastal lowlands in the western sector and steep mountainous terrain in the eastern region. Elevations across the study area range from 0 to 1,853 m above sea level, with most urban activities concentrated in the coastal lowlands. According to the Köppen-Geiger climate classification, this area is categorized as having a tropical rainforest climate (Af) [26].

This study applies spatial restrictions based on the Padang City Spatial Plan 2010-2030 [27], limiting the analysis to lowland areas designated as cultivation zones and built-up areas. Upland areas, including protected forests,



Fig. 1. Study Area

were systematically excluded from all stages of the analysis, including NDVI calculation, LST extraction, and Urban UTFVI modeling; in other words, these areas were categorized as areas without urbanization activity. This was also done to reduce high spatial heterogeneity due to the influence of changes in surface topography factors [28]. By normalizing the data distribution based on urban lowland zones, the UTFVI analysis becomes statistically more robust and more relevant for identifying heat vulnerability patterns in residential areas and economic activity centers. This approach allows for the evaluation of thermal interactions between impermeable surfaces and urban vegetation in a comparable spatial context in Padang City.

NDVI and LST Computation. This study employed Landsat 8 Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS) satellite imagery processed using Precision and Terrain Correction (L1TP). Multispectral band 4 (red) and band 5 (near-infrared) were utilized to derive surface reflectance and calculate the NDVI, while thermal band 10 was used for LST estimation. Although the original spatial resolution of the Thermal Infrared Sensor (TIRS) band is 100 m, the data have been resampled to 30 m by the United States Geological Survey (USGS) in the distributed products, ensuring consistency with the Operational Land Imager (OLI) bands and enabling integrated spatial analysis. All satellite images used in this study were geometrically corrected spatial datasets and were freely downloaded from the USGS portal(https://earthexplorer.usgs.gov/).

Spatial delimitation was applied by restricting the analysis to lowland areas designated as built-up and cultivation zones in accordance with Padang City Regulation No. 3. 2019. Protected areas including protected forests, conservation zones, and designated greenbelt areas, were systematically excluded from the analysis to prevent thermal bias and to maintain analytical consistency. Detailed specifications of the Landsat 8 OLI/TIRS data utilized in this study are provided in Table 1.

Spatial delimitation was implemented by restricting the analysis to lowland areas designated as built-up and cultivation zones. Protected forests (such conservation areas, and greenbelt zones) were excluded using shapefile boundaries as spatial masks to prevent thermal bias and to ensure analytical consistency.

Landsat 8 OLI/TIRS imagery was used to extract surface temperature for the period 2015-2024. The temperature retrieval procedure followed the methodology outlined in the Landsat 8 User Handbook [29] and consisted of several sequential steps. First, the digital number (DN) values of TIRS band 10 were converted into top-

Table 1

Specification of Landsat 8 OLI/TIRs

Path/Row	Sensor	Date	Spatial Resolution
127/ 061	Landsat 8 OLI/TIRS	01/07/2015 22/07/2017 25/05/2019 11/05/2020 04/07/2022 25/07/2024	30 meter

of-atmosphere (TOA) spectral radiance, using the following equation (2.1).

$$Reflektan = \rho\lambda' = M\rho * Qcal + A\rho \quad (2.1)$$

where $\rho\lambda'$ represents the top-of-atmosphere (TOA) reflectance uncorrected for the solar elevation angle, $M\rho$ is a specific band multiplicative rescaling factor), $A\rho$ is a specific band additive rescaling factor dan $Qcal$ denotes the pixel value expressed as digital numbers (DN).

Furthermore, the satellite brightness temperature is derived from the spectral irradiance values [29], using the following equation (2.2):

$$T = \frac{K2}{In(\frac{K1}{L\lambda}+1)} - 273.15 \quad (2.2)$$

where T represents temperature (in Kelvin, subsequently converted to degrees Celsius), $L\lambda$ denotes the spectral radiance value of the thermal band (band 10), $K1$ dan $K2$ are the calibration constants obtained from the Landsat 8 metadata.

To obtain the final LST from Landsat 8 imagery, surface emissivity (ε) must be calculated [30], which can be derived using the following equation (2.3):

$$(\varepsilon) = 0.004 \times pv\ (NDVI) + 0.986 \quad (2.3)$$

where ε denotes land surface emissivity and, pv represents the proportion of vegetation.

NDVI values were used to determine land surface emissivity (ε) following by [30]. Subsequently, NDVI was further employed to calculate the proportion of vegetation (Pv) [31]. The NDVI calculation applied in this study is expressed by the following equation (2.4 and 2.5) [32].

$$NDVI = \frac{\text{band 5} - \text{band 4}}{\text{band 5+band 4}}) \quad (2.4)$$

$$Pv = \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}}) \quad (2.5)$$

The final LST was calculated using the following equation (2.6):

$$LST = \frac{BT}{\{1 + [(\lambda BT/\rho)\ ln\ \epsilon\lambda]\}} \quad (2.6)$$

where BT denotes brightness temperature, λ represents the wavelength of the emitted radiation for each band, ρ is the Boltzmann constant (1.38×10^{-23} J/K), and ε refers to land surface emissivity [33].

NDVI was utilized as a key parameter in estimating land surface emissivity, which subsequently constitutes an essential component in the calculation of final LST. The role of NDVI is critical because this index is directly associated with the estimation of vegetation proportion (Pv) and land surface emissivity (ε), two fundamental factors that determine the accuracy of land surface temperature measurements. In addition to its function in LST computation, NDVI was also employed in this study to evaluate the spatial relationship between vegetation cover and variations in land surface temperature. Theoretically, NDVI values range from -1 to 1, where values approaching 1 represent dense vegetation cover, while values close to zero or negative indicate sparsely vegetated areas or non-vegetated surfaces.

Urban Thermal Field Variance Index (UTFVI). To evaluate the spatial intensity of urban thermal stress and ecological quality, this study employed the UTFVI. UTFVI is designed to quantify the deviation of local land surface temperature from the mean temperature of the study area, thereby enabling the identification of zones experiencing relatively high thermal stress [34, 35]. UTFVI was calculated using the following equation (2.7):

$$UTFVI = \frac{LST_i - LST_{mean}}{LST_{mean}} \quad (2.7)$$

where LST_i represents the land surface temperature of the i-th pixel, LST_{mean} denotes the average land surface temperature of the entire study area.

Higher UTFVI values indicate the presence of the Strongest UHI class and correspond to the worst ecological quality, whereas lower UTFVI values represent more stable thermal conditions and Excellent ecological status. To facilitate interpretation and spatial analysis, UTFVI values

were classified into six UHI presence classes and Ecological Evaluation Index (EEI) categories (35, 36], as presented in Table 2.

Table 2

Classification of Urban ecological condition

UHI Presence	UTFVI	EEI
None	<0	Excellent
Weak	0-0.005	Good
Middle	0.005-0.010	Normal
Strong	0.010-0.015	Bad
Stronger	0.015-0.020	Worse
Strongest	>0.020	Worst

This classification enables the identification of zones experiencing extreme thermal stress and facilitates the evaluation of temporal changes in the spatial distribution of heat stress. The UTFVI approach was selected because it effectively captures urban thermal heterogeneity that cannot be identified through analyses based solely on average LST values. By integrating UTFVI results with NDVI and LST dynamics, this study provides a comprehensive analytical framework for assessing the relationships among ecological degradation, urban surface structure, and the intensity of thermal stress in Padang City.

3. Results and Discussion

Analysis of NDVI-LST dynamics in the lowlands of Padang City, 2015-2024). The analysis results indicate that the relationship between NDVI-LST in the lowland areas of Padang City consistently exhibits a negative correlation throughout the observation period from 2015 to 2024 (Fig 2.A and 2.B). This pattern underscores the role of vegetation as a key regulator of surface temperature, particularly through evapotranspiration and shading mechanisms, which are highly relevant in the context of a tropical humid coastal city.

Statistically, this negative relationship is confirmed by spatial linear regression analysis conducted for each year of observation (Fig 2.C). In 2015, the NDVI and LST relationship exhibited the strongest explanatory power, with a coefficient of determination (R^2= 0.554), indicating that increases in NDVI were significantly associated with reductions in surface temperature (slope = -8.04). This condition reflects a lowland landscape that remained relatively responsive to vegetation influences, characterized by an average surface temperature of 28.61 ^{0}C and a mean NDVI value of 0.51 (Table 3).

In 2017 and 2019, the direction of the relationship remained negative, but its strength declined (R^2 values of 0.3803 and 0.3528, respectively), even though the mean surface temperature reached relatively high levels (up to 29.95 ^{0}C in 2017). This indicates that the aggregate increase in vegetation density (mean NDVI of 0.56-0.58) was not sufficient to fully offset the intensification of urban activities and the expansion of impervious surfaces in the lowland areas. In other words, thermal control began to shift from vegetation dominance toward a combination of urban morphological factors and anthropogenic activities.

Interestingly, during the 2020 period-coinciding with the COVID-19 pandemic and the implementation of Large-Scale Social Restrictions [37] in Padang City average surface temperature declined to 28.18 ^{0}C, even though the strength of the NDVI-LST relationship further weakened (R^2=0.3207). This finding aligns with previous studies showing reductions in land surface temperature intensity during COVID-19–related activity restrictions, primarily due to decreased anthropogenic heat emissions, and indicating that reduced human mobility can weaken the NDVI–LST relationship despite relatively stable vegetation cover [38-40].

Table 3

Mean LST and NDVI in the lowlands of Padang City, 2015–2024

Years	Mean LST (0C)	Mean NDVI
2015	28.61	0.51
2017	29.95	0.58
2019	28.94	0.56
2020	28.18	0.54
2022	27.41	0.56
2024	29.84	0.50

In 2022, the mean surface temperature reached its lowest value during the study period (27.41 ^{0}C), followed by a slight strengthening of the NDVI-LST relationship (R^2 = 0.378). This condition suggests that urban vegetation including intra-urban green open spaces still possesses significant thermal mitigation capacity when anthropogenic pressures are relatively reduced. Conversely, in 2024, a renewed increase in mean surface temperature (29.84 ^{0}C) was accompanied by a decline in average NDVI (0.50) and a further weakening of the NDVI and LST relationship (R^2 = 0.33), indicating heightened thermal stress associated with the expansion of built-up areas and the intensification of anthropogenic activities in the post COVID-19 period.

Overall, these results indicate that the NDVI–LST relationship remains directionally stable but progressively weakens in strength over time as the complexity of the urban surface increases. This trend reflects a fragmentation

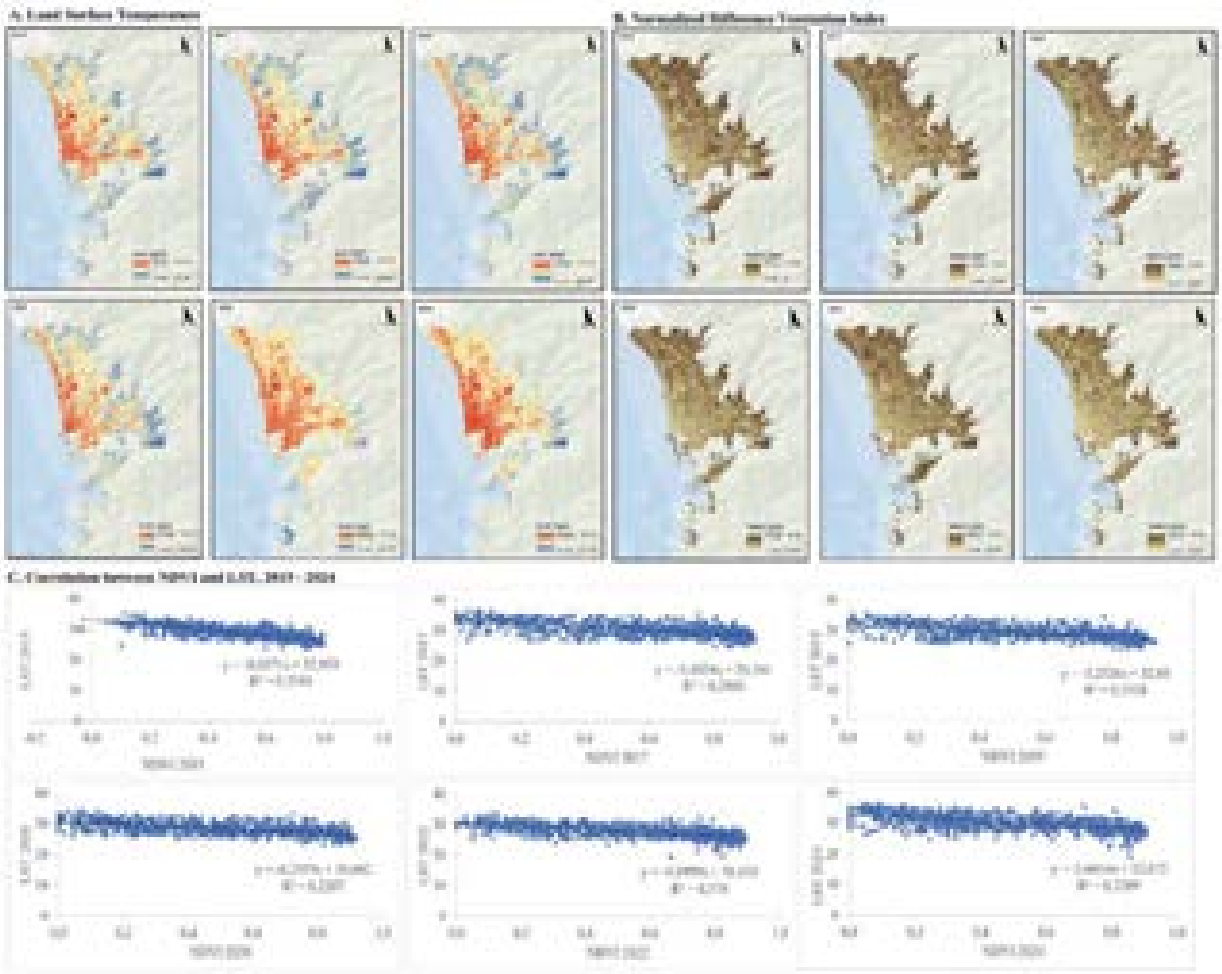


Fig. 2. A) LST dynamics, 2015-2024, B) NDVI dynamics, 2015-2024, C) Correlation between NDVI and LST, 2015-2024.

of the role of vegetation in regulating surface temperature, alongside the growing structural complexity of the city and the dominance of impervious materials. By restricting the analysis to lowland areas and excluding highland forest zones, this study captures thermal variability that is more representative of actual urban conditions. The spatial patterns of LST generated in this subsection subsequently provide a quantitative basis for evaluating thermal stress levels and heat vulnerability using the UTFVI approach.

Urban Ecological Quality of The Lowland Areas of Padang City. The UTFVI analysis provides a comprehensive perspective on urban ecological quality by integrating presence of UHI classifications with the EEI. Unlike mean surface temperature analysis, UTFVI emphasizes relative thermal variance, enabling the precise identification of heat concentrations within a microclimatic context. Annual pixel data from 2015 to 2024 indicates that the thermal structure of Padang city lowland areas is consistently dominated by two contrasting extreme classes: 'None-Excellent' and 'Strongest-Worst', which cumulatively account for over 65-70% of the total observation area (table 4 and table 5).

During the initial phase (2015-2019), the 'None-Excellent' class exhibited a moderate expansion trend, with area increases of 0.34% (2015-2017) and peaking at 1.95% in 2019 (187,159 pixels). The spatial distribution in Fig.3.(a, b, c) shows that this zone is concentrated in the urban periphery with continuous vegetation, indicating that natural cooling mechanisms remained effective. This finding is supported by a strong negative correlation between NDVI and LST during this period (2015 = 0.5544), confirming the crucial role of green cover in mitigating surface heat. However, the 'Strongest-Worst' class continued to dominate the urban core, reflecting densely built-up zones that are structurally susceptible to heat entrapment.

A significant disruption occurred in 2020, marked by a -1.97% contraction in the 'None-Excellent' class and a 1.00% increase in the 'Strongest-Worst' class. This anomaly coincided with the implementation of Large-Scale Social Restriction policies. Despite the macro-level decline in human activity, UTFVI results reveal that areas dominated by impermeable materials maintained their heat stress intensity. This phenomenon reinforces the argument regarding the high thermal

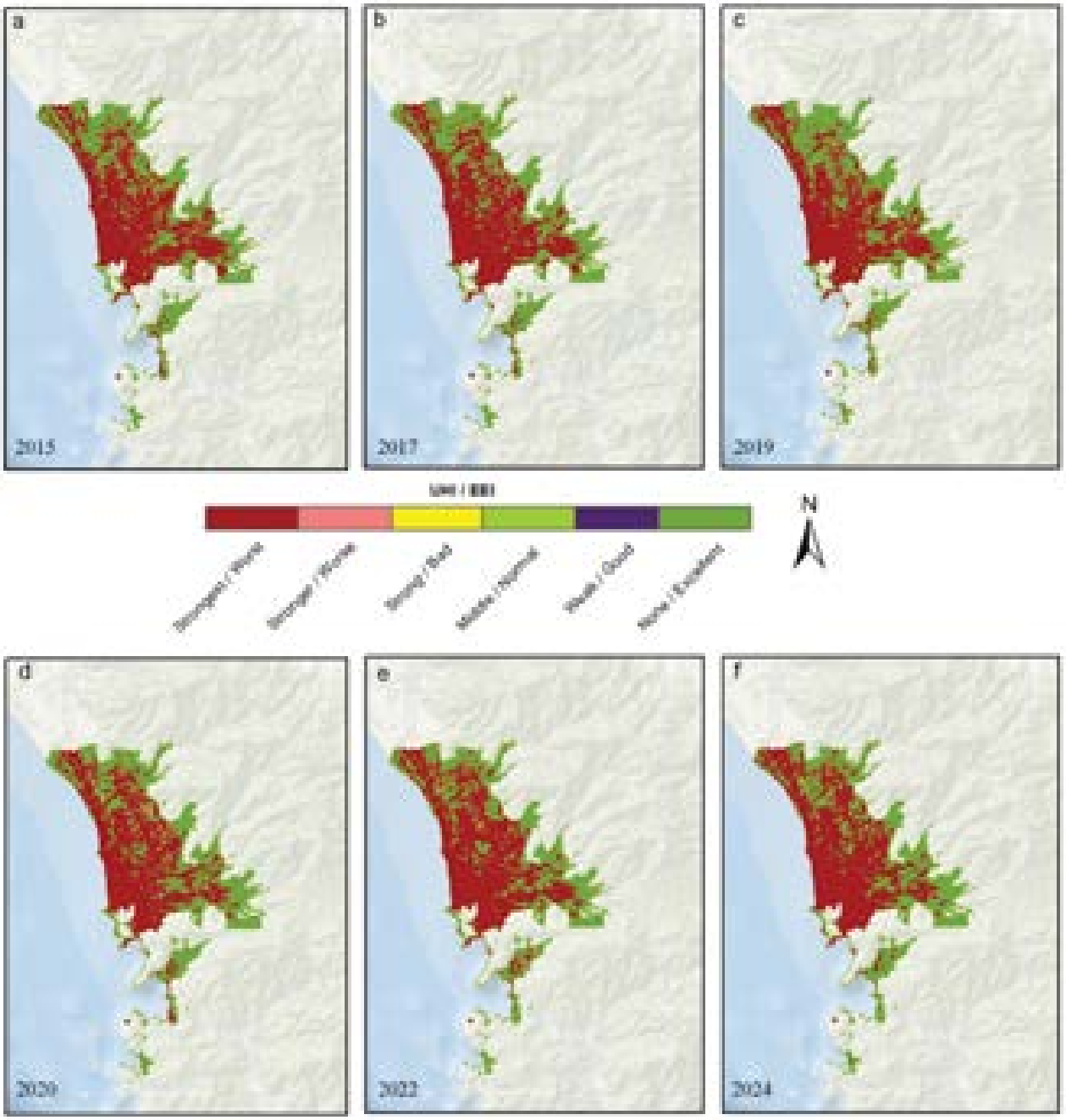


Fig. 3. Spatial distribution of UTFVI in the lowlands of Padang City, 2015-2024

inertia of concrete and asphalt materials, which retain heat longer, aligning with findings by [41, 42] that physical material characteristics are more determinant of surface heat retention than short-term fluctuations in anthropogenic emissions. This condition is exacerbated by the morphology of high-density built-up areas-such as residential and commercial areas-which significantly contribute to increasing surface temperatures through the concentration of heat-absorbing materials [43].

In the post-pandemic period (2020-2024), thermal ecological quality showed a more aggressive degradation. The 'Strongest-Worst' class surged by 3.20% between 2020 and 2022, reaching its peak at 135,739 pixels in 2024, while the 'None-Excellent' class experienced a significant decline. Spatially (Fig.3: d. e. f), the massive expansion of the 'Strongest-Worst' zone (red) indicates 'heat leakage' and ecological fragmentation, where green space connectivity is increasingly severed by built-up expansion. This is further evidenced by the decline in the coefficient of determination in the NDVI-LST correlation (2024 = 0.3289), suggesting that sporadic vegetation additions are no longer sufficient to reduce heat in areas dominated by impermeable surfaces.

Overall, the degradation of the thermal environmental quality in Padang City is structural. The consistent growth of the 'Worst' zone indicates a weakening capacity of the urban ecological

Table 4

UTFVI distribution in the lowlands of Padang City, 2015–2024

		Years (in pixel 30x30 meter)					
UHI Presence	EEI	2015	2017	2019	2020	2022	2024
None	Excellent	179,47	180,6	187,16	180,53	170,3	174,273
Weak	Good	7,575	7,269	7,526	7,681	7,77	6,837
Middle	Normal	7,647	6,994	7,018	7,873	7,628	6,848
Strong	Bad	7,063	6,595	6,707	7,768	7,567	6,305
Stronger	Worse	7,303	6,454	6,423	7,619	7,411	6,224
Strongest	Worst	127,168	128,31	121,39	124,76	135,5	135,739

Table 5

Percentage change of UTFVI in the lowlands of Padang City, 2015–2024

		Percentage Pixel Change (%) in UTFVI, 2015-2024				
UHI Presence	EEI	2015-2017	2017-2019	2019-2020	2020-2022	2022-2024
None	Excellent	0.34	1.95	-1.97	-3.03	1.17
Weak	Good	-0.09	0.08	0.05	0.03	-0.28
Middle	Normal	-0.19	0.01	0.25	-0.07	-0.23
Strong	Bad	-0.14	0.03	0.32	-0.06	-0.38
Stronger	Worse	-0.25	-0.01	0.36	-0.06	-0.35
Strongest	Worst	0.34	-2.06	1	3.2	0.07

system to neutralize heat stress. Future mitigation strategies can no longer rely solely on preserving existing vegetation; instead, they must include radical spatial interventions such as surface material albedo control and the optimization of urban morphological design to enhance the thermal resilience of tropical coastal cities.

4. Conclusion

This study demonstrates that the thermal ecological environmental quality in the lowlands of Padang City is undergoing increasingly structural degradation. Although the negative correlation between vegetation density and surface temperature remains consistent, its strength continues to weaken annually, indicating the limitations of urban vegetation in neutralizing accumulated heat amidst massive built-up land expansion. The binary dominance between high ecological quality areas in the peripheries and extreme heat stress in the city center reflects a sharp and persistent thermal polarization across the city's lowland landscape.

Anomalies identified in 2020 reveal that the reduction in anthropogenic activities during the pandemic was insufficient to improve structural thermal conditions due to high thermal inertia in impermeable materials and non-vegetated areas. Post-pandemic (2022-2024), the escalation of heat stress has shown a more aggressive pattern, with heat penetration beginning to encroach into buffer zones through ecological fragmentation mechanisms. These findings emphasize that UHI mitigation can no longer rely solely on vegetation conservation; rather, it necessitates integrated spatial interventions encompassing surface material control, urban morphological design, and the strengthening of blue-green infrastructure to enhance the thermal resilience of tropical coastal cities.

Внесок авторів: всі автори зробили рівний внесок у цю роботу
Конфлікт інтересів: автори повідомляють про відсутність конфлікту інтересів
Декларація про використання генеративного штучного інтелекту: Автори використовували інструменти генеративного штучного інтелекту (GenAI) для допоміжної роботи: моделі ChatGPT-5.5 (OpenAI, 2026) виключно для мовного редагування, структурного впорядкування тексту; Grammarly – для перевірки правильності перекладу тексту, а також для виправлення граматичних та стилістичних помилок. Усі результати роботи з цими інструментами були ретельно контрольовані, перевірені та, за необхідності, відредаговані авторами. Весь науковий контент, матеріали та висновки були створені авторами. Автори несуть повну відповідальність за зміст та цілісність публікації.

Authors Contribution: All authors have contributed equally to this work
Conflict of Interest: The authors declare no conflict of interest

Declaration of use of generative artificial intelligence: The authors utilized generative artificial intelligence (GenAI) tools in a supportive capacity: the ChatGPT-5.5 model (OpenAI, 2026) exclusively for language editing and structural text organization; Grammarly – to verify the correctness of the text translation, as well as to correct grammatical and stylistic errors. All outputs from these tools were carefully supervised, reviewed, and, where necessary, edited by the authors. All scientific content, materials, and conclusions were created by the authors. The authors retain full responsibility for the content and integrity of the publication.

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Міська динаміка термічного стресу в тропічному прибережному місті: аналіз дистанційного зондування в місті Паданг, Індонезія

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АНОТАЦІЯ

Феномен міського теплового острова (МТО) є однією з ключових екологічних проблем сучасних міст, що негативно впливає на тепловий комфорт населення, збільшує витрати енергії на охолодження та підвищує ризики для здоров'я. У тропічних регіонах ці наслідки посилюються високими температурами, інтенсивною сонячною радіацією, швидкою урбанізацією та деградацією природних буферних зон. Особливо це характерно для тропічних прибережних міст, де зміни землекористу-

вання суттєво порушують мікрокліматичний баланс. Дослідження присвячене місту Паданг (Індонезія), яке протягом останнього десятиліття зазнало значної урбанізації, що супроводжувалася перетворенням природних і сільськогосподарських територій на житлову та комерційну забудову й формуванням локальних теплових аномалій. Для аналізу просторово-часової динаміки використано багаточасові супутникові знімки Landsat 8 OLI/TIRS за 2015–2024 рр. Дослідження охоплювало прибережні низовини, виключаючи гірські ліси для мінімізації топографічного впливу. Щільність рослинності оцінювали за індексом NDVI, температуру поверхні землі (LST) визначали за тепловими інфрачервоними каналами після калібрування даних і розрахунку випромінювальної здатності поверхні. Для оцінки теплового стресу застосовано індекс варіації міського теплового поля (UTFVI), який класифікує екологічний стан території за шістьма категоріями. Результати показали стійку негативну кореляцію між NDVI та LST, що підтверджує важливу роль рослинності у зниженні температури поверхні. Водночас сила цього зв'язку поступово зменшувалася, що свідчить про ослаблення охолоджувального ефекту зелених насаджень через розширення непроникних поверхонь. Під час пандемії COVID-19 у 2020 році середня температура поверхні тимчасово знизилася до 28,18 °C внаслідок скорочення антропогенних теплових викидів. Проте аналіз UTFVI засвідчив подальше розширення зон із найвищим рівнем теплового стресу, особливо в центральній частині міста, а після пандемії (2022–2024) їх площа досягла максимуму. Отримані результати свідчать про структурне погіршення теплоекологічного стану Паданга та підкреслюють необхідність інтеграції синьо-зеленої інфраструктури, використання матеріалів із вищим альбедо й оптимізації міського планування для підвищення теплової стійкості в умовах зміни клімату та подальшої урбанізації.

ІНФОРМАЦІЯ ПРО СТАТТЮ :

Рукопис надійшов
30 січня 2026

Отримано після рецензування
10 березня 2026

Затверджено до друку
25 травня 2026

Опубліковано онлайн
30 травня 2026

Ключові слова:

UHI, UTFVI, EEI, LST, екологічна якість, NDVI, дистанційне зондування, тропічне місто, прибережне місто, місто Паданг.

ПРАВИЛА ОФОРМЛЕННЯ МАТЕРІАЛІВ, ЩО ПОДАЮТЬСЯ ДО «Вісника Харківського національного університету імені В.Н. Каразіна. Серія "Геологія. Географія. Екологія"»

До «Вісника Харківського національного університету імені В.Н. Каразіна. Серія «Геологія. Географія. Екологія», приймаються наукові статті обсягом біля 40 тис. знаків, присвячені дослідженням у галузях геології, геохімії, гідрогеології, географії, економічної та соціальної географії, екології, а також суміжних дисциплін. Матеріали можуть бути представлені українською або англійською мовами. Перевага надається англомовним статтям. Рішення про публікацію приймається редакційною колегією „Вісника", при цьому кожна стаття рецензується двома вченими-фахівцями у даній тематиці. Українськими авторами стаття надсилається українською мовою і перекладається після рецензування.

Матеріали подаються в електронному вигляді та надсилаються на електронну пошту geoeco-series@karazin.ua. Електронна версія оформлюється у форматі Microsoft Word, шрифт Times New Roman, розмір 14, міжрядковий інтервал 1,5, всі поля по 2 см, відступ для абзацу – 0,75 см. **Жирним** шрифтом виділяються підзаголовки у статті. Ілюстрації, включаючи графіки і схеми, мають бути розміщені безпосередньо в тексті, а також подані окремими файлами. Неприпустимо включати підписи до самого рисунка. У статті не дозволяється використовувати чужі рисунки, а також власні, що раніше були опубліковані, без письмового дозволу авторів або журналу-правовласника. Виключеннями є геологічні карти та власні схеми (із обов'язковим посиланням на джерело). Скрізь, де можливо, доцільніше використовувати графіки, а не таблиці. Орієнтація сторінок – книжкова. Вирівнювання слід робити по ширині сторінки. Якщо стаття українською, є необхідним дублювання підписів до рисунків та назв таблиць і діаграм англійською.

Оригінальна *дослідницька стаття* (*оглядові статті* до розгляду не приймаються) має бути підготовлена з використанням **IMRAD**-структури (introduction, methods, results, and discussion) та містити такі основні елементи:

Вступ (Постановка проблеми у загальному вигляді та її зв'язок із важливими науковими чи практичними завданнями, актуальність, мета, об'єкт та предмет дослідження; Аналіз останніх досліджень і публікацій, в яких започатковано розв'язання порушеної проблеми, на які спирається автор, обов'язково повинна бути розглянута література за останні п'ять років, включена до наукометричних баз Scopus та WoS; Виділення невирішених раніше частин загальної проблеми, яким присвячується стаття).

Методи

Результати

Дискусія і висновки

Для статей необхідно вказати *УДК*, подати *назву* (до 10 слів), *анотацію* (1800-2500 знаків) та *ключові слова* (8-10).

На окремому аркуші надається *інформація про авторів* (прізвище, ім'я та по-батькові, повна назва організації, посада, вчений ступінь і звання, поштова адреса, телефон, e-mail, ORCID) українською й англійською мовами. *Список використаних джерел* оформлюється мовою оригіналу згідно міжнародного стандарту APA (American Psychological Association). Перелік повинен містити не менше ніж 20 посилань. Також обов'язково необхідно додавати номери DOI (за наявності). Літературні посилання нумеруються в порядку цитування в тексті, номер посилання пишеться у квадратних дужках. Не допускаються посилання на неопубліковані роботи, звіти, дисертації, підручники та навчальні посібники.

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– структурованість (наявність обов'язкових елементів: *вступ* (передумови, актуальність, мета, об'єкт та предмет дослідження); *методи*; *результати*; *висновки; ключові слова*).

Після реферату необхідно навести *References* – перекладений англійською список використаних джерел. В кінці джерела вказується мова оригіналу в квадратних дужках, наприклад [in Ukrainian].

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Methods

Results

Discussion and **conclusions**

For articles, it is necessary to indicate the *UDC*, submit a *title* (up to 10 words), *abstract* and *keywords* (8-10).

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A detailed *abstract* in English is also required, that follows the IMRAD standard structure. The abstract should

- be between 2500-3500 characters,
- represent the content (represent the research findings and the article's main content),
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Зразок оформлення статті :

UDC 528.8+551.4

Integrating remote sensing and aeromagnetic data for lithological and structural lineaments mapping in Abu Ghaylan - Kiklah - Tighrinna, northwest Libya

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ABSTRACT

Problems Statement and Purpose. Libya is the fourth-largest country in Africa and the seventeenth-largest country in the world with area of 1,759,540 sq. km. Most of Libya is located in the Sahara Desert and known for being the driest and most remote regions with limited accessibility. …

***Keywords**: Libya, Remote Sensing, Digital Elevation, Lineaments, Lithological Mapping, Aeromagnetic, …*

Introduction

Integration approach of multi-source data can improve geological interpretation and provide detailed information on unexplored areas [1–3]. The remote sensing satellites (sensors) can detect and map geological surface based on the spectral and spatial resolution [4, 5]. …

References

Thiele, S.T., Lorenz, S., Kirsch, M., Cecilia Contreras Acosta, I., Tusa, L., Herrmann, E., Möckel, R., Gloaguen, R. (2021). Multi-Scale, Multi-Sensor Data Integration for Automated 3-D Geological Mapping. Ore Geology Reviews, *136, 104252. DOI: https://doi.org/10.1016/j.oregeorev.2021.104252*

Authors Contribution: All authors have contributed equally to this work
Conflict of Interest: The authors declare no conflict of interest
Declaration of use of generative artificial intelligence: The authors utilized generative artificial intelligence (GenAI) tools in a supportive capacity: Elicit was employed to assist in reviewing the references, and QuillBot was used to aid in language revision. All outputs from these tools were carefully supervised, reviewed, and, where necessary, edited by the authors. The authors retain full responsibility for the content and integrity of the publication.

Інтеграція дистанційного зондування та аеромагнітних даних для картографування літологічних і структурних ліній в Абу-Гайлан - Кікла - Тігрінна, північно-західна Лівія

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У 1970-х роках Центр промислових досліджень у Лівії розпочав створювати геологічні карти всіх лівійських земель, отриманих з аналогових (друкованих) аерофотознімків і геологічних польових поїздок у деякі доступні місця. …

***Ключові слова**: Лівія, дистанційне зондування, цифровий рельєф, лінеаменти, літологічне картування, аеромагнітний, інтеграція даних, …*

Список використаних джерел

Thiele, S.T., Lorenz, S., Kirsch, M., Cecilia Contreras Acosta, I., Tusa, L., Herrmann, E., Möckel, R., Gloaguen, R. (2021). Multi-Scale, Multi-Sensor Data Integration for Automated 3-D Geological Mapping. Ore Geology Reviews, *136, 104252. DOI: https://doi.org/10.1016/j.oregeorev.2021.104252*

Внесок авторів: всі автори зробили рівний внесок у цю роботу
Конфлікт інтересів: автори повідомляють про відсутність конфлікту інтересів
Декларація про використання генеративного штучного інтелекту: автори використовували інструменти генеративного штучного інтелекту (GenAI) для допоміжної роботи: Elicit було залучено для допомоги в перегляді літератури, а QuillBot – для допомоги в редагуванні тексту. Усі результати роботи з цими інструментами були ретельно контрольовані, перевірені та, за необхідності, відредаговані авторами. Автори несуть повну відповідальність за зміст та цілісність публікації.

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Наукове видання

ВІСНИК ХАРКІВСЬКОГО НАЦІОНАЛЬНОГО УНІВЕРСИТЕТУ імені В. Н. КАРАЗІНА

серія
«ГЕОЛОГІЯ. ГЕОГРАФІЯ. ЕКОЛОГІЯ»

Випуск 64

ЗБІРНИК НАУКОВИХ ПРАЦЬ

Українською та англійською мовами

Редактор *В. Г. Суярко*
Технічний редактор *О. В. Чуєнко*
Комп'ютерне верстання *І. М. Дончик, О. С. Чистякова*
Відповідальний за випуск *В. Г. Суярко*

Підписано до друку 25.05.2026 р. Формат 60x84/8. Папір офсетний.
Друк цифровий. Ум. друк. арк. 50,1. Обл.-вид. арк. 62,6.
Наклад 100 пр. Зам. № 31/26.

Видавець та виготовлювач
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Свідоцтво суб'єкта видавничої справи ДК № 3367 від 13.01.09.