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Assessment of groundwater vulnerability within the cross-border areas of Ukraine and Poland

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ABSTRACT

Problem statement. The growing global trend of groundwater consumption and excessive groundwater abstraction in many parts of the world requires an accurate and comprehensive assessment of the potential for groundwater resource development. The EU-WATERRES international project has begun developing a concept for coordinated management and harmonized monitoring of groundwater resources in the transboundary areas of Ukraine and Poland. Studying groundwater's natural protection status or vulnerability is a priority, as groundwater pollution has become a significant environmental problem in recent decades due to the growth of industrial production and agricultural activities.

Study objective is to analyze the existing materials on the natural protection of groundwater within the study area and to quantify the vulnerability of the main useful aquifer (MUA) to surface pollution in the cross-border Polish-Ukrainian area.

Methodology involves the quantitative method of groundwater vulnerability assessment by calculating the time of pollutant penetration into the aquifer through the aeration zone using the modified Bindemann formula and GIS.

Research results. Studies have shown that the most vulnerable among MUA there is an unconfined alluvial Quaternary horizon (alQ) of the Syan and Dniester River basins. Throughout its entire development, its vulnerability corresponds to the "very high" category because of pollution from the surface caused by precipitation filtration. The Upper Cretaceous aquifer (K2) is less vulnerable. The groundwater of this horizon in the Polish part of the cross-border area is more vulnerable - here the vulnerability corresponds to the categories "very high" and "high". In the Ukrainian part, the Upper Cretaceous aquifer is characterized by better natural hydrogeological conditions and is less vulnerable to pollution. The Lower Neogene aquifer, which has a limited distribution on the slopes of the Western Bug-Syan River watershed within Roztochia, is the least vulnerable to pollution as compared to the others. The lithological composition of the aeration zone and the thickness of weakly permeable and practically impermeable rocks have a decisive impact on the filtration time and vulnerability of groundwater to pollutants from the surface by infiltration.

Scientific novelty of the research. For the first time, a quantitative assessment of the vulnerability of the MUAs for the Polish-Ukrainian cross-border area was carried out. The use of the results of this assessment will facilitate the adoption of appropriate management decisions for the comprehensive protection of transboundary groundwater, prevention of its pollution, and reduction of anthropogenic impact.

Keywords*: groundwater vulnerability, transboundary aquifer, main aquifer, Polish-Ukrainian cross-border area.*

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Introduction. The coordinated management of transboundary groundwater resources (TGR) is becoming increasingly important worldwide to minimize adverse transboundary impacts. Due to the growing global trend of groundwater consumption, exceeding groundwater abstraction in many parts of the world, an accurate and comprehensive assessment of the development potential of groundwater resources is needed [13, 23]. The global identification of TGR began in 2000 under the coordination of the International Shared Aquifer Resources Management (ISARM) under the auspices of UNESCO. Since its foundation, ISARM has launched a number of global and regional initiatives aimed at inventorying transboundary aquifers and encouraging states to work together in a mutually beneficial and sustainable manner.

The International Groundwater Resources Assessment Centre (IGRAC) is developing a global information system that facilitates the availability of relevant information and knowledge on groundwater resources worldwide, with a focus on developing countries. Since 2003, IGRAC specialists have been focusing on the assessment of transboundary aquifers (TBAs) and groundwater monitoring for their sustainable development and coordinated management. It is estimated that there are 591 TBAs in the world, including 317 in Europe [15].

The issue of studying and continuously monitoring the state of water resources for transboundary water basins, which involves establishing international cooperation in this area, is extremely relevant. Therefore, within the framework of the international project "EU-WATERRES: European Integrated Management System for Transboundary Groundwater Resources and Anthropogenic Hazards", funded by Iceland, Liechtenstein, and Norway through the European Economic Area Grant Fund and the Norwegian Regional Cooperation Grant Fund, the development of a concept for coordinated management and harmonized monitoring of TGR for the pilot area of the Vistula River basin (Western Bug and San subbasins) and part of the Dnister River basin has been started.

Among many aspects of the project research tasks, the study of the natural protection or vulnerability of groundwater is a priority, as groundwater pollution has become a significant environmental problem in recent decades due to the increasing rate of industrial production and agricultural activities. Knowledge on areas that are particularly vulnerable to pollution helps to properly assess the state of transboundary groundwater, prevent its pollution, make informed decisions on its protection, and foresee the consequences of decisions.

Analysis of recent research and publications. Various models and approaches for assessing the vulnerability of aquifers have been developed and tested in the world over the past three to four decades. Methods for determining the vulnerability of an aquifer can be divided into two standard categories - qualitative and quantitative. According to V.M. Shestopalov and others [10], there are four main types of methods for assessing the protection and vulnerability of groundwater: hydrogeological zoning methods, index-rating methods (qualitative methods), parametric methods, and modeling methods (quantitative methods). The latter is based on mathematical modeling of the processes of filtration and migration of pollutants, taking into account the physical and chemical interactions in the "migrant-water-rock" system and the main barrier properties of the geological environment.

Qualitative methods based on indices combined with Geographic Information Systems (GIS) are the most frequently used models, as they facilitate the interpretation of results for users. With their help, maps are created that describe zones with different levels of vulnerability, which ease the decision-making procedure for monitoring and preserving groundwater quality [10]. The advantages and disadvantages of the most popular index-based methods (DRASTIC, GOD, and SI) are analyzed and presented in [14].

Currently, there is no specific definition of the concept of groundwater vulnerability, as well as a standard technique for its, since the concept of groundwater vulnerability is not an absolute property, but a complex indicator. Therefore, researchers applying the DRASTIC method often adapt it to their data or tasks [16]. To ensure that the GIS technique can provide an effective way of working with the large amount of spatial data used in the DRASTIC model, the groundwater vulnerability map can be confirmed with an additional layer of nitrates or any other specific contamination values [4, 21]. Some researchers use two different index-based methods to compare results [11]. The DRASTIC method can be used both for regional studies and for processing a significant array of data as the authors did for assessing the vulnerability and risk of groundwater pollution on a pan-African scale [19]. The cartographic model was also confirmed by data on the concentration of nitrates in groundwater.

Qualitative methods for assessing groundwater vulnerability include the hydrogeological zoning method, which is based on the qualitative categorization of vulnerability for the respective selected zones. It has been used to assess the vulnerability of groundwater in urbanized areas [1, 5]. Thanks to hydrogeological zoning by the degree of vulnerability of aquifers and taking into account potential sources of groundwater pollution, researchers can assess and visualize the risks of disasters [3].

According to S. Levoniuk and I. Udalov, all methods have a common drawback as they are aimed solely at assessing the degree of protection (vulnerability) of groundwater from surface pollution. The authors believe that it is also necessary to take into account the impact of deep highly mineralized groundwater on the quality of drinking water in the active water exchange zone, given the current geodynamic activity of the earth's crust in the context of intensive technogenesis. To this end, researchers have proposed their own methodology for the rational combination of geo-environmental indicators, which allows for determining the degree of comprehensive protection of groundwater from the pollution of both anthropogenic (surface) and natural (neotectonic) nature [6].

In Ukraine, one of the most widely used methods for assessing the protection and vulnerability level to groundwater pollution is the Goldberg method [2]. It takes into account natural factors and stipulates assigning a certain number of conditional points or an index to an aquifer, the criteria for determining which are set by the researcher. To assess the security of unconfined groundwater, the methodology provides for the determination of the sum of scores, which consists of a score for the thickness of the entire aeration zone and scores for each low-permeability layer belonging to one of three lithological groups in the structure of the aeration zone: group a - if the poorly permeable layer contains sandy loam and light loam, b - loam, and c - heavy loam and clay). A qualitative assessment of the protection level of confined groundwater is to assign it to conditional protection categories, which directly depend on the thickness of the overlying water-resistant layer.

Quantitative methods for assessing groundwater vulnerability involve calculating the time (rate) of penetration of a particular pollutant into an aquifer, taking into account natural properties of the aeration zone and migration properties of the pollutant. Ukrainian researchers I. Sanina and N. Liuta used the following formula to calculate the time of penetration through layered rocks [8]:

$$A_0 = \frac{m_0}{k_0},$$

where A_0 is the penetration time, days;

m_0 - thickness of the low-permeable layer, m;

k_0 - filtration coefficient of the low-permeability layer, m/day.

According to the authors, such studies are somewhat generalized, especially given that there is very little data on determining the filtration coefficients of rocks in the aeration zone for the territory of Ukraine in general. And to calculate the time of contamination penetration through the rocks of the layered strata, which is most typical for the aeration zone section, the authors recommend using a technique that ensures the heterogeneous strata are brought to a single permeability estimate by its calculating for a less permeable layer [8].

In Poland, researchers often estimate vertical seepage of contamination using the formulas of Witczak and Żurek, Bachmat and Collin, and Bindeman. However, these formulas often give unreasonable differences in the results obtained. Tadeusz Macioszczyk made an attempt to level these differences by proposing a modified Bindeman formula. In his opinion, supported by specific examples, the estimate of vertical seepage in the unsaturated zone obtained with this modified formula becomes clearly more rational [18]. The problem of discrepancies between these equations continues to be discussed by researchers [17]. To establish the most reliable way to determine the time of vertical seepage, the team of authors, in addition to the four widely used equations, used the modeling method employing the HYDRUS 1D numerical code. Calculations and modeling showed quite variable results of migration time for conservative contamination depending on the chosen equation, but the greatest similarity of results obtained by the model is demonstrated by the Macioszczyk equation [20].

Study objective is to analyze the existing materials on the natural protection of groundwater within the study area and to quantify the vulnerability of the main useful aquifer (MUA) to surface pollution in the cross-border Polish-Ukrainian area.

Methodology – quantitative method of groundwater vulnerability assessment by calculating the time of pollutant penetration into the aquifer through the aeration zone using the modified Bindemann formula and GIS.

Scientific novelty of the research. For the first time, a quantitative assessment of the vulnerability of the MUAs for the Polish-Ukrainian cross-border area was carried out. The use of the results of this assessment will facilitate the adoption of appropriate management decisions for the comprehensive protection of transboundary groundwater, prevention of its pollution, and reduction of anthropogenic impact.

Research results. IGRAC identified only one TGR in the Polish-Ukrainian border area within the Vistula River basin, Bug River sub-basin (in Ukraine, the Western Bug River) [15]. In the EU-WATERRES project, the study covered the transboundary areas of the San sub-basin (within the San River basin) and the Dnister River basin (within the water management area from the source to the mouth of the Stryi River) (Fig. 1). The area of the study site is as follows: within the transboundary basin of the Western Bug River – 15 575 km^2, the San River – 4 569 km^2, and the Dnister River – 5 929 km^2.

The choice of the study area was based on the allocation of hydrogeological units of transboundary nature - transboundary aquifers (TBA). The hydrogeological identification and definition of TBA were carried out by harmonizing hydrogeological spatial data between neighboring countries, spatial diversification of the development and properties of usable aquifers, and mapping of the hydroisohypsum surface and aquifer thickness.

The transboundary nature of an aquifer was determined based on the criterion of the potential for

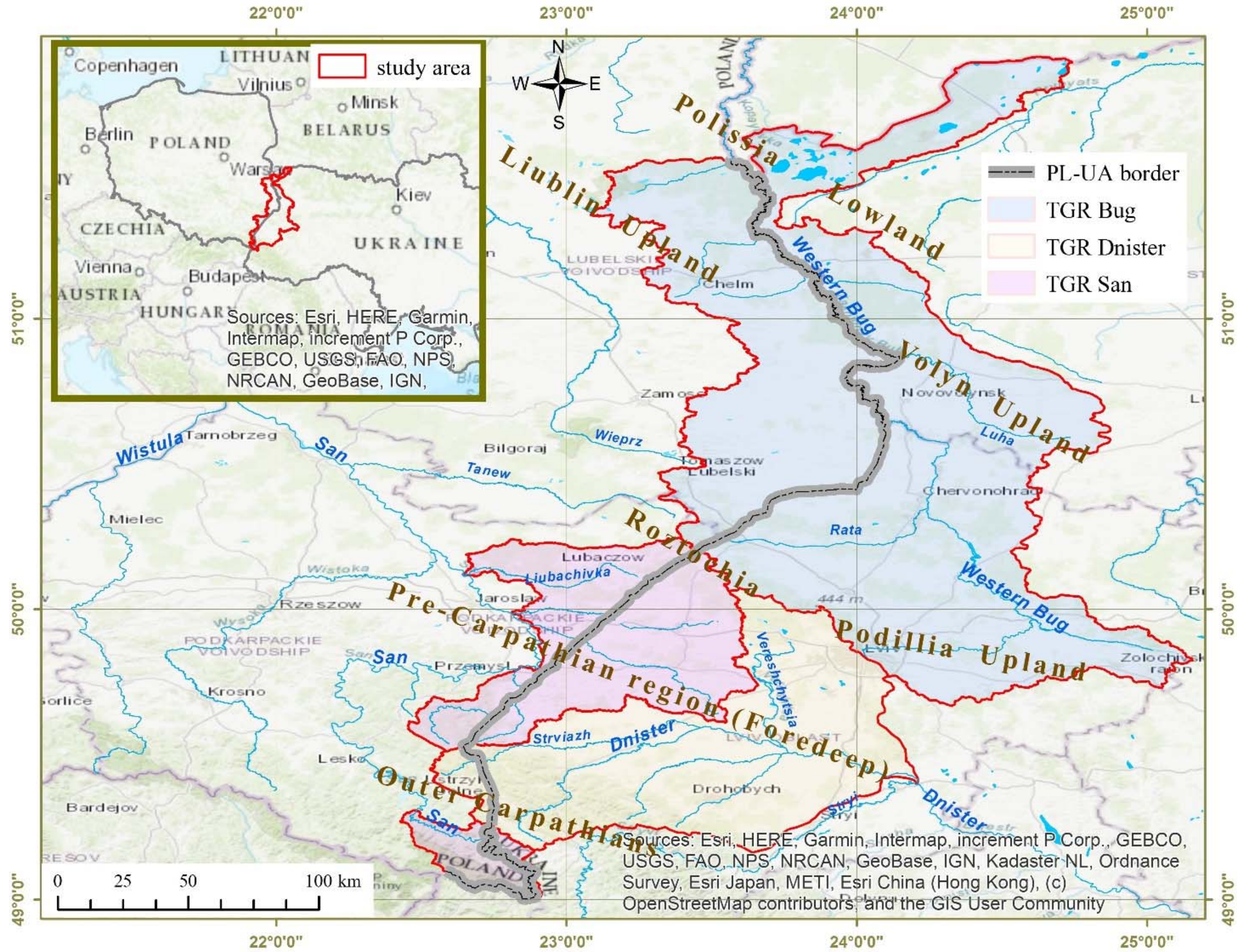

Fig. 1. Location of the research area

groundwater exchange between neighboring countries. The absence of groundwater exchange is stated in the case of the detection of a "dense" boundary of groundwater flow, which is formed by watercourses draining a certain aquifer and watersheds [7, 22].

The approach to the division of hydrogeological units in Poland and Ukraine is similar and consists in zoning the first usable aquifer. Unified rules for the division of hydrogeological units within the TGR have been developed for the first usable aquifer.

The unified hydrogeological map of the Bug, San, and Dnister River basins identified the main useful aquifers (MUAs) that meet the following criteria:

– provide water yield of more than 50 m^2/day;

– have a total thickness of 5 meters or more;

– demonstrate a consistent occurrence over an area of at least 20 km^2 (5 km^2 is allowed if the hydrogeological conditions are well identified and differentiated in space);

– wells with a flow rate of more than 5 m^3/hour.

The MUAs of the Poland and Ukraine border area include an unconfined aquifer of alluvial Quaternary sediments (alQ); a confined aquifer of Lower Neogene sediments (N1) and a confined-unconfined aquifer of Upper Cretaceous sediments (K2) (Fig. 2). The total area of the MUAs is 2,973 km^2 in alluvial deposits (alQ), 16,070 km^2 in Upper Cretaceous deposits (K2), 400 km^2 in Upper Cretaceous-Quaternary deposits in Poland (K2-Q), and 1,724 km^2 in Lower Neogene deposits in Ukraine (N1).

Before choosing a method and performing the groundwater vulnerability assessment within the Polish-Ukrainian pilot site, we analyzed previous studies regarding the Ukrainian part of the territory. In Ukraine, a qualitative assessment of groundwater protection was performed using the Goldberg methodology to compile and publish "Maps of Natural Groundwater Protection of the Ukrainian SSR" scaled 1:200,000 encompassing the whole territory of Ukraine. We present the map of natural groundwater protection in the Lviv region, which was analyzed and modified using GIS [9]. For convenience, we have separated the distribution of unconfined and confined groundwater into separate schemes.

Figure 3 shows that unconfined aquifers are classified as unprotected in the vast majority of the area of distribution, as they do not have a waterproof overlay and lie shallow from the ground surface, depending on the relief, the depth varies from 2-4 to 5-

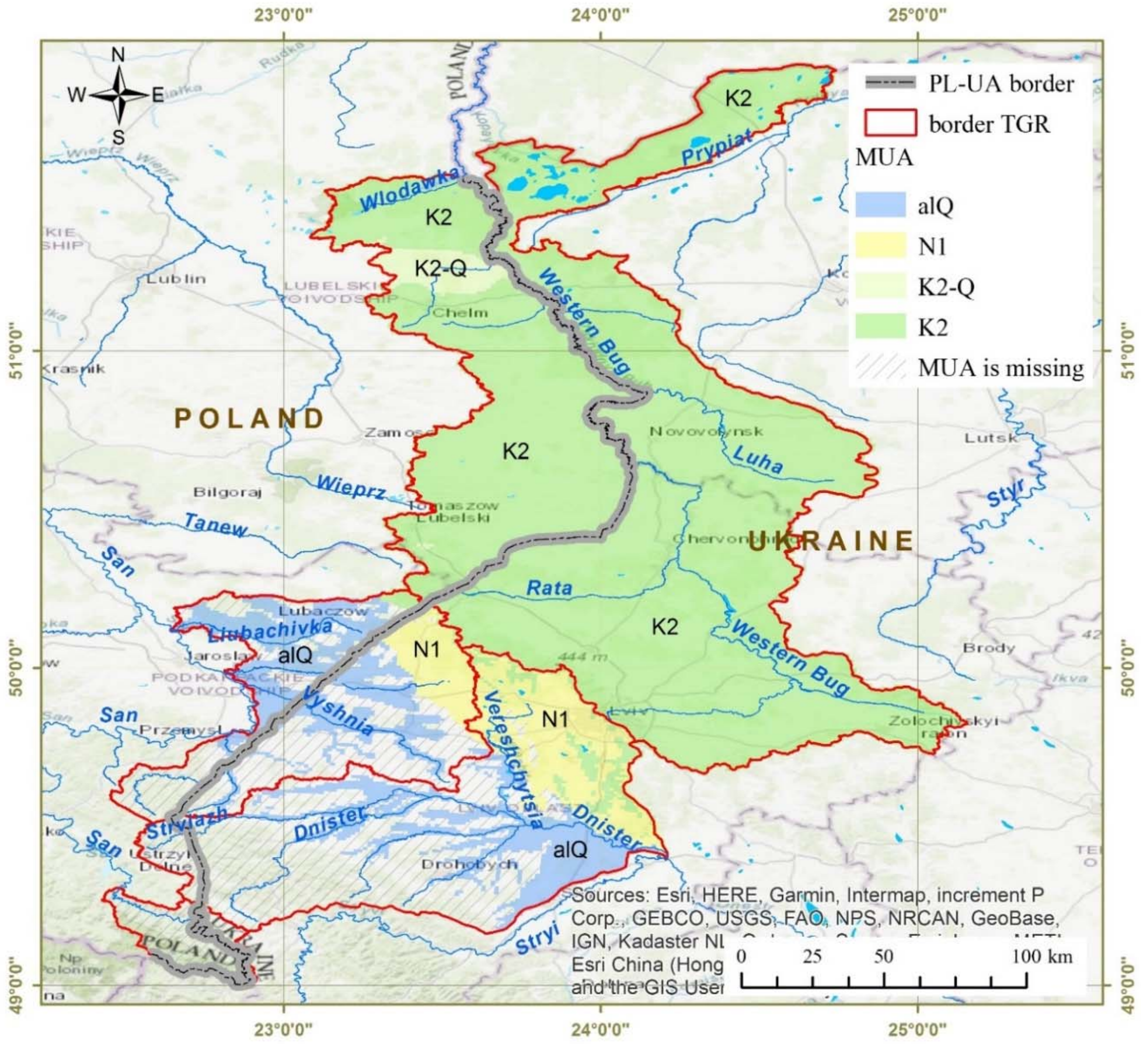

Fig. 2. Map of the main useful aquifers

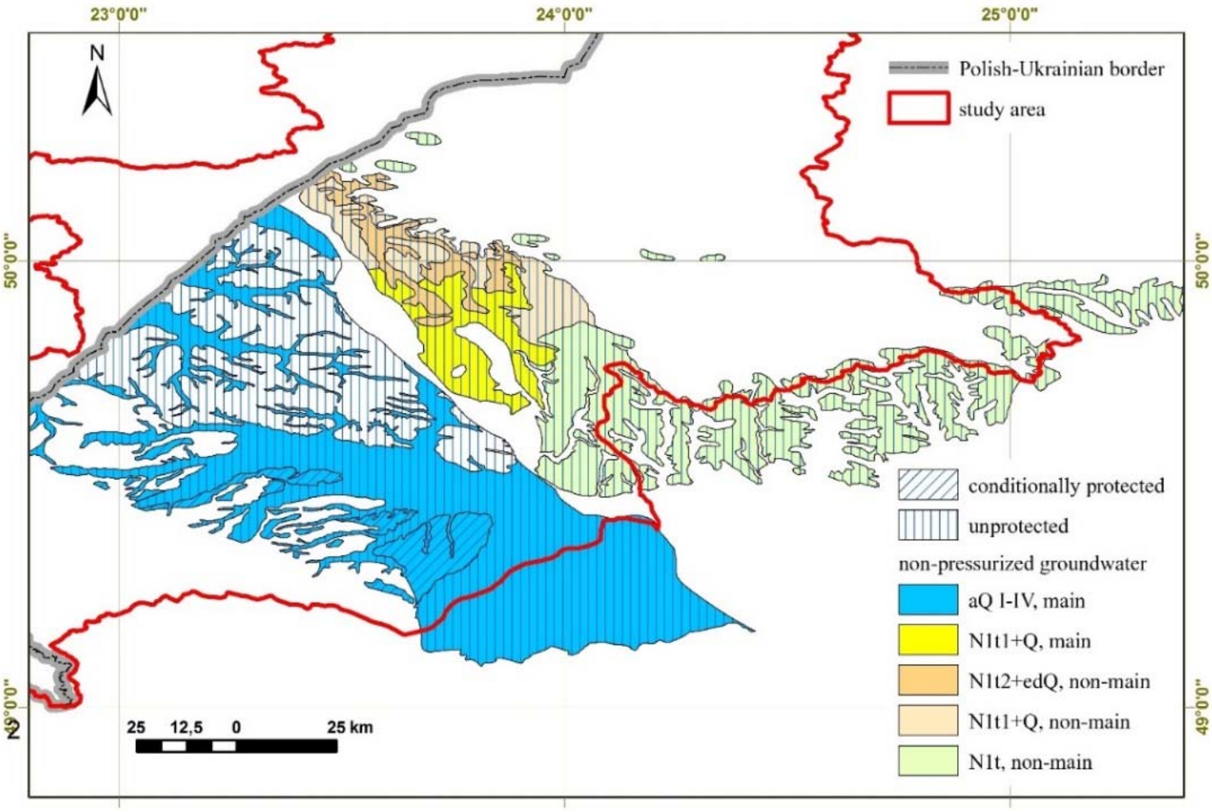

Fig. 3. Map of natural protection of unconfined groundwater in Lviv region (based on Tkachuk et al., 1986)

10 meters. Only minor locally widespread alluvial Quaternary waters within the Pre-Carpathian Artesian Basin, which occur at a depth of >10 m (10-25 m) and have clay loam rocks in the aeration zone, are qualified as conditionally protected (Fig. 3).

Figure 4a shows the distribution of the main confined aquifers associated with the Upper Tortonian (N1t2; N1ts), Lower Tortonian (N1t1), and Up-

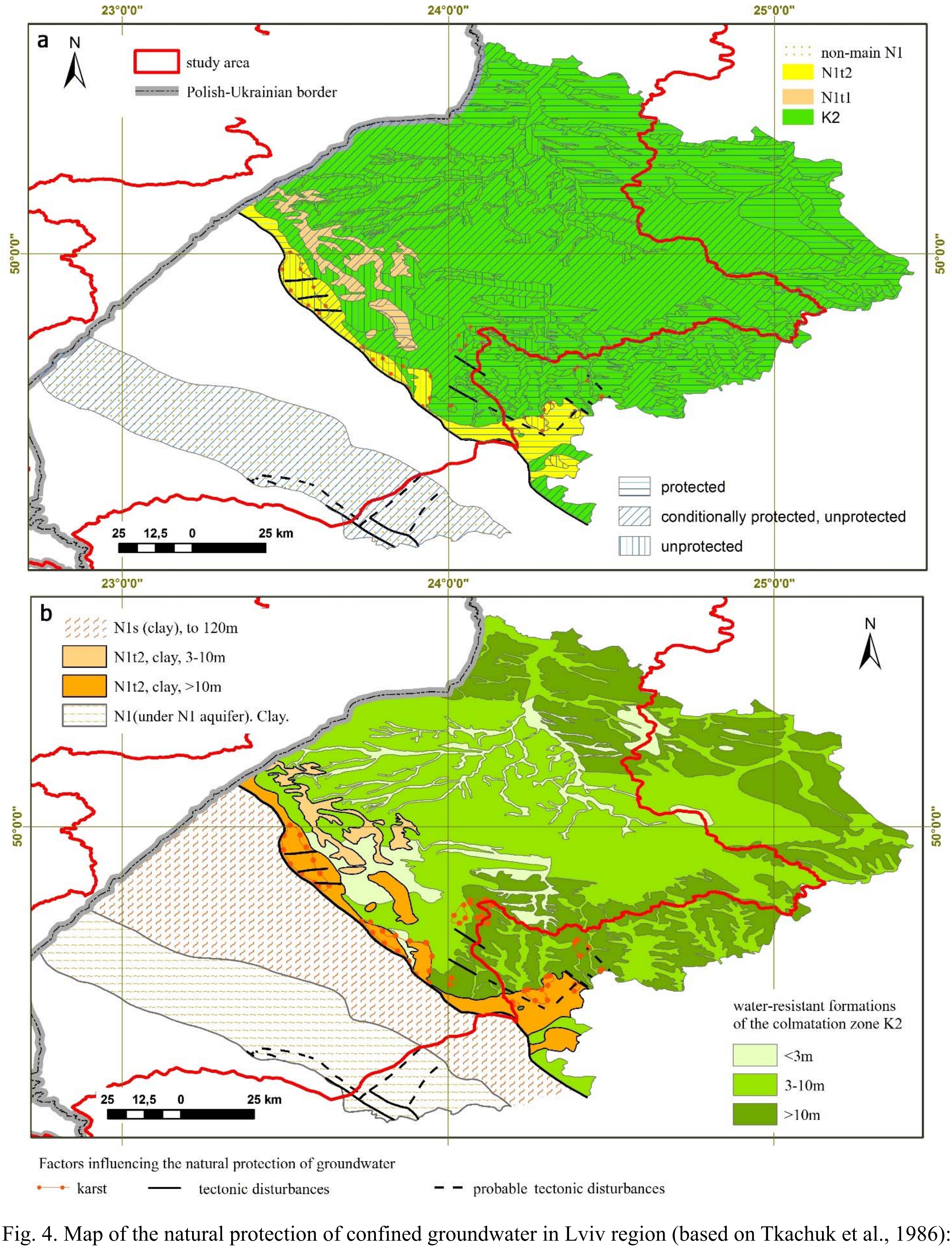

Fig. 4. Map of the natural protection of confined groundwater in Lviv region (based on Tkachuk et al., 1986):
a - distribution of the main confined aquifers with an indication of their protection class;
b - distribution of the main confined aquifers with an indication of their capacities.

per Cretaceous (K2) deposits, as well as the non-main Lower Neogene aquifer (N1), indicating their protection class. Figure 4b shows the distribution of waterproof layers with their capacities. The qualitative assessment of the natural protection of confined groundwater is based mainly on the presence of overlying impermeable and slightly permeable rocks and their thickness. If the thickness of clay and marl rocks is up to 3 m, the aquifer is classified as "unprotected", from 3 m to 10 m - "conditionally protected" and >10 m - "protected". Additional factors influencing the assessment of groundwater vulnerability to contamination are the areas of development of surface karst forms and zones of tectonic fractures in the thickness of pre-Quaternary sediments.

Confined groundwater is mostly unprotected or conditionally protected. Only groundwater of the Lower Neogene deposits is classified as protected, except for the areas of karst development, which worsens their hydrogeological conditions. This is due to the absence of sufficiently thick water-resistant layers in the aeration zone above the aquifers. The so-called "colmatage zone", which is a lithologically calcified doughy chalk, sometimes sandy, plays the role of the upper water-bearing layer in the aeration zone for the Upper Cretaceous aquifer. Hydrodynamically, it separates the Quaternary and Upper Cretaceous aquifers and plays an important role in protecting the MUAs from contamination.

Within the pilot area of the Polish-Ukrainian territory, we quantified the vulnerability of the MUAs using the modified Bindemann formula for calculating the time of water infiltration through the aeration zone [18]:

$$t = \frac{m \times W_0}{\sqrt[3]{i^2 \times k_z}},$$

where t – is infiltration time of precipitation through the aeration zone, days;

m – thickness of the aeration zone, m;

W_0 – volumetric moisture of sediments in the aeration zone,

i –annual effective infiltration, $i = P \times k*$, m/day (where P – is precipitation indicator, m/day; $k*$ –coefficient of effective infiltration);

k_z –vertical infiltration coefficient of the aeration zone, m/day.

The values of volumetric moisture (Wo), effective infiltration coefficients ($k*$), and vertical infiltration of the aeration zone (k_z), which depend on the lithological composition of the aeration zone, are taken from Witczak and Żurek [24].

Precipitation indicator P for individual TGR was calculated by us according to the site "Meteopost. Weather statistics. Climate data by year and month" (https://meteopost.com/weather/climate/). For the Western Bug and San River basins, it is 0.00196, and for the Dnister basin, it is 0.00207 m/day.

In the process of fulfilling the project tasks, the following vulnerability classification was adopted based on the time of pollution migration from the surface:

Time of pollution migration from the surface, years	**Vulnerability**
< 5	Very high
5-25	High
25-50	Average
50-100	Low
>100	Very low

It should be noted that taking into account the experience of Sanina I. and Liuta N., with a heterogeneous structure of the aeration zone, we performed calculations only for the water-resistant layers combined into one [8].

The process of vulnerability study can be presented as a series of step-by-step plots of the distribution of power, volumetric moisture content of sediments, annual effective infiltration, and vertical infiltration coefficient of the aeration zone of the MUAs (Fig. 5).

Figure 6 shows the results of the assessment of the vulnerability of the MUAs in the Polish-Ukrainian border area.

The figures of the step-by-step construction of the vulnerability map show that the value of the volume humidity of the rocks in the aeration zone correlates with the infiltration time the most. A direct correlation between higher value of the volume humidity and longer time of pollutant filtration from the surface to groundwater is observed. It is well known that the highest values of volumetric moisture content are characterized by weakly permeable and practically waterproof rocks.

The correlation between the aeration zone's thickness and the filtration time through it is somewhat weaker. Hence, taking into account the previous conclusion, it follows that the infiltration time is influenced rather by the thickness of the weakly permeable or practically impermeable rocks than by the total thickness of the aeration zone. The direct dependence of the filtration time on the vertical infiltration coefficient of the aeration zone is also evident, and less obvious with the annual effective infiltration. The precipitation rate undoubtedly affects filtration but is not decisive in this process.

The analysis of the performed plots shows that the vulnerability of 43.5% of the MUAs area is very high, 37.9% - high, 6.2% - average, 5.9% - low, and only 6.4% - very low.

The most vulnerable among the MUAs is the unconfined alluvial Quarterly horizon (alQ). It is widespread in the river valleys of the Dnister and the San with their tributaries within the Carpathian Foredeep, lies shallowly from the earth's surface, and is not covered by thick waterproof layers. The same vulnerability is also characteristic of the aquifer of undivided Upper Cretaceous-Quaternary sediments (K2-Q) in Poland for similar reasons. Over the entire area of their distribution, they fully (100%) correspond to the "very high" vulnerability category to surface pollution.

The Upper Cretaceous aquifer (K2) is less vulnerable, which is of the greatest importance for meeting consumer needs in the transboundary area and covers the entire Bug TGR area from the Polissia Lowland in the north to the Podillia Upland in the south. Vulnerability of 36% of the area is very high, 50% is high, 8.2% is medium, 4% is low, and only 2% of the area falls into the category of very low. It should be noted that the groundwater of this horizon in the part of the study area, the Upper Cretaceous aquifer is characterized by somewhat better natural hydrogeo-

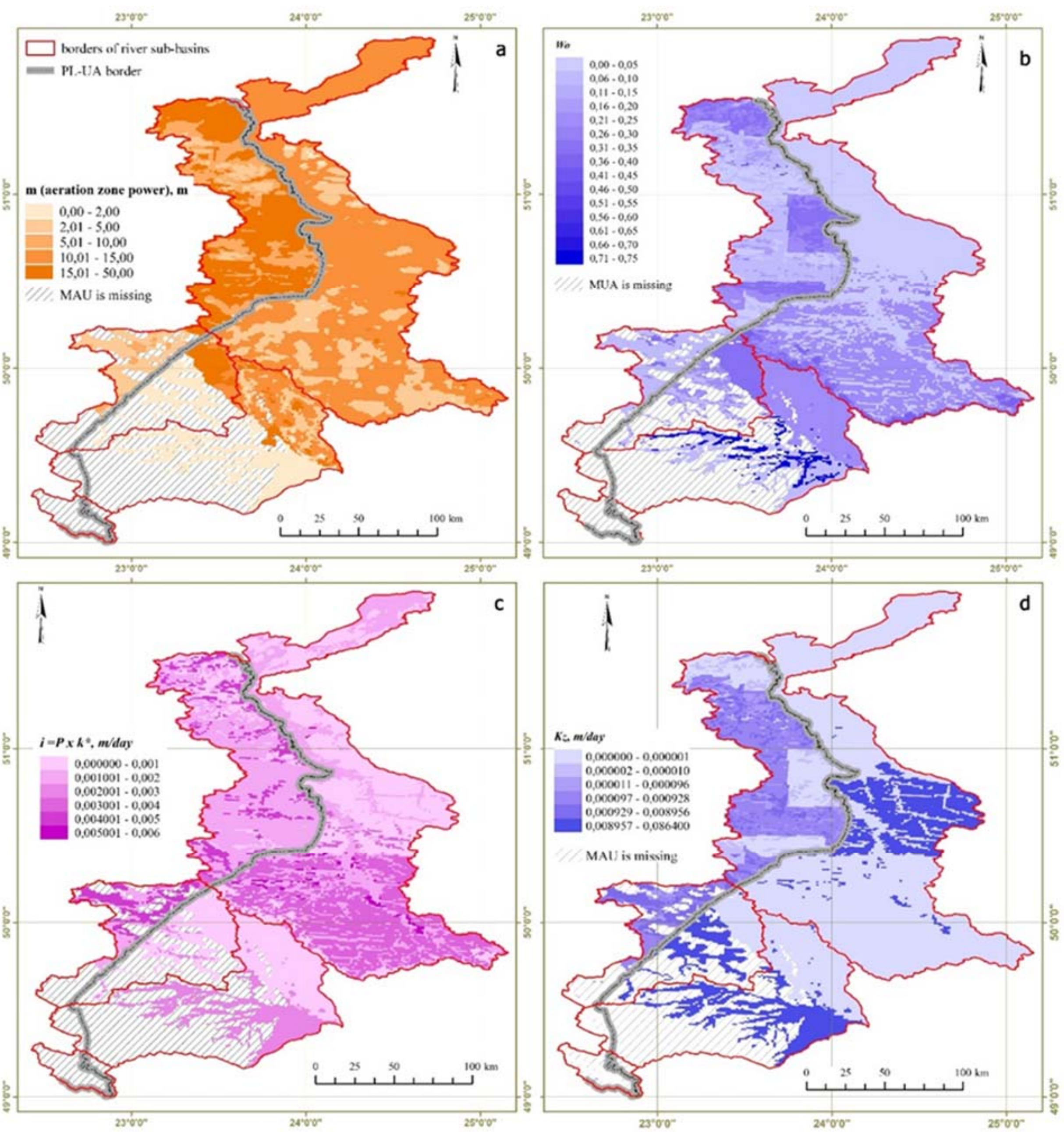

Fig. 5. Step-by-step construction of the MUAs vulnerability map: a - distribution of aeration zone capacity; b - distribution of volumetric moisture content of aeration zone sediments; c - annual effective infiltration for aeration zone sediments; d - distribution of vertical infiltration coefficient of aeration zone sediments

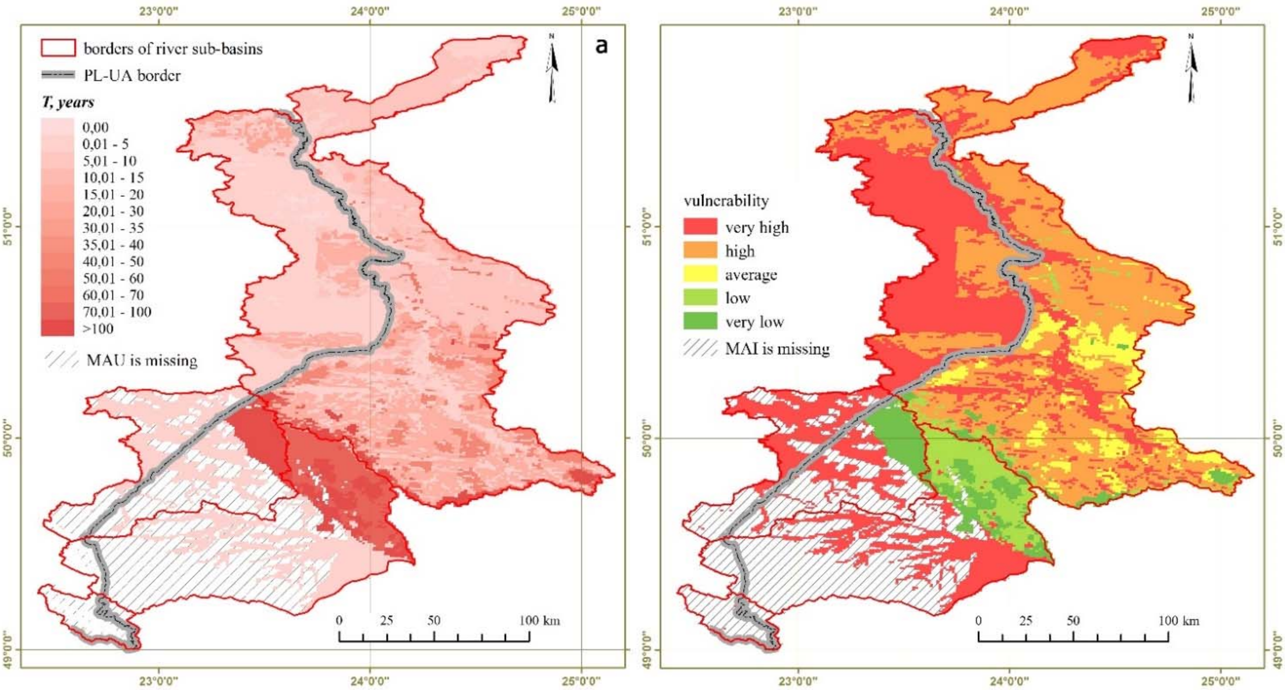

Fig. 6. The map of the vulnerability of the MUAs for the Polish-Ukrainian border area:
a - by the time of pollution infiltration from the surface; b - by the vulnerability class

logical conditions (higher aquifer thickness, presence of a "colmatage zone"). There is a tendency for vulnerability to decrease from north to south: from very high in Polissia to high and medium in Volyn-Podillya. On the slopes of Roztochia, groundwater of the Upper Cretaceous horizon (K2) is sufficiently protected (very low vulnerability). However, in this region, the role of the MUA is taken over by the Lower Neogene aquifer (N1), which lies hipsometrically higher. In fact, the Lower Neogene aquifer (N1), which has a limited distribution on the slopes of the Western Bug and San Rivers watershed within the Roztochia Upland, is the least vulnerable to pollution compared to the others. The vulnerability of about 60% of the area is very low, 37% is low, and only 3% is very high.

Conclusions. The conducted studies have shown that the lithological composition of the aeration zone and the thickness of weakly permeable and practically impermeable rocks have a decisive influence on the filtration time and, accordingly, the assessment of groundwater vulnerability to pollutant penetration from the surface by filtration. Such an assessment of the vulnerability of the MUAs, performed by the quantitative method, correlates well enough with the analyzed map of the qualitative assessment of the natural protection of groundwater.

It has been established that the MUAs in the study area are poorly protected and therefore require constant monitoring of their condition. The use of the results of this assessment will facilitate the adoption of appropriate management decisions for the comprehensive protection of transboundary groundwater, prevention of its pollution, and reduction of anthropogenic impact.

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Оцінка вразливості підземних вод в межах транскордонних територій України та Польщі

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В рамках міжнародного проекту “EU-WATERRES: Європейська інтегрована система управління транскордонними підземними водними ресурсами та антропогенними небезпеками” розпочато розробку концепції скоординованого управління та гармонізованого моніторингу транскордонних водоносних горизонтів для пілотної ділянки басейну ріки Вісла (суббасейни річок Західний Буг, Сян) та частини басейну ріки Дністер. Вивчення природної вразливості підземних вод стало важливою частиною досліджень, оскільки забруднення підземних вод в останні десятиліття є вагомою екологічною проблемою через зростання темпів промислового виробництва та сільськогосподарської діяльності. Авторами проаналізовано матеріали вивчення природної захищеності підземних вод у межах досліджуваної території попередніми дослідниками та проведена кількісна оцінка вразливості основного корисного водоносного горизонту (ОКВГ) до забруднення з поверхні за модифікованою формулою Біндемана і використанням ГІС. Дослідження показали, що найбільш вразливим серед ОКВГ є безнапірний алювіальний четвертинний горизонт (alQ) басейнів річок Сяну та Дністра. На всій площі свого розвитку його вразливість відповідає категорії "дуже висока" до забруднення з поверхні за рахунок фільтрації атмосферних опадів. Менш вразливим є верхньокрейдовий водоносний горизонт (K2). Підземні води цього горизонту на польській частині транскордонної території є більш вразливими - тут вразливість відповідає категоріям "дуже висока" і "висока". На українській частині верхньокрейдяний водоносний горизонт характеризується кращими природними гідрогеологічними умовами і є менш вразливим до забруднення. Нижньонеогеновий водоносний горизонт, який має обмежене поширення на схилах вододілу річок Західний Буг-Сян в межах Розточчя, є найменш вразливим до забруднення порівняно з іншими.

Ключові слова*: підземні води, вразливість, транскордонний водоносний резервуар, основний корисний водоносний горизонт, польсько-українське транскордоння.*

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