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ECOLOGICAL ASSESSMENT OF SURFACE WATER CONDITIONS OF THE DANUBE RIVER

Purpose. To provide a comprehensive environmental assessment and forecasting of the condition of surface waters of the Danube River within the Ukrainian section (Reni – Izmail – Vylkove), with a focus on the dynamics of key hydrochemical indicators over the period 2010–2024. Special attention is given to the influence of anthropogenic factors, including intensive navigation, industrial pressure, and the environmental consequences of military actions, which have altered the hydrological regime and deteriorated water quality.

Methods. System analysis, statistical data processing, distribution analysis, and regression modeling were employed to assess retrospective dynamics and predict future trends in water quality. The information was sourced from long-term monitoring data collected at observation stations in the cities of Kiliya, Vylkove, and the river's mouth.

Results. The analysis focused on six key water quality indicators: phosphates, ammonium, sulfates, chlorides, biochemical oxygen demand over five days (BOD_5), and dissolved oxygen concentration. Phosphate and ammonium compounds exhibited seasonal fluctuations, attributed to discharges of organic and agricultural origin. Sulfate concentrations were found to be highly variable, combining both natural and anthropogenic sources, while chloride levels remained stable with signs of chronic influence. The analysis of BOD_5 and dissolved oxygen indicators suggests a potential for self-purification, although certain periods revealed deterioration in oxygen balance, particularly due to localized organic overload and disrupted hydrodynamics. Developed regression models allowed the identification of relationships between hydrological changes, port activity intensity, and pollution levels.

Conclusions. The main environmental issues of the lower Danube were identified as organic and mineral pollution, eutrophication, decreased oxygen levels, hydromorphological changes, and threats posed by armed conflict. Despite these challenges, the river retains a capacity for partial self-recovery, especially under reduced anthropogenic pressure. Restoring ecological balance will require the implementation of systematic monitoring, modernization of wastewater treatment facilities, effective pollution source management, and Ukraine's active participation in international environmental regulatory mechanisms, such as the Danube Commission. The modeling results can be used to forecast water environment conditions in both peacetime development and post-war recovery scenarios.

KEY WORDS: *Danube River, surface waters, environmental monitoring, phosphates, ammonium, sulfates, chlorides, dissolved oxygen, BOD$_5$, anthropogenic impact, forecasting, war*

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Introduction

The Danube River, as one of Europe's major transboundary watercourses, plays a critical ecological, hydrological, and socio-economic role in the region. Its lower reach within Ukraine encompasses the dynamic and biologically rich Danube Delta, a UNESCO Biosphere Reserve that supports high biodiversity and essential ecosystem services. However, this area faces increasing environmental pressure from agricultural runoff, municipal discharges, industrial activities, and intensified navigation.

In recent years, the ecological integrity of the Danube has been further challenged by hydromorphological alterations, climate variability, and, since 2022, the environmental consequences of military conflict. These factors have altered the river's water quality, disrupted natural flow regimes, and increased the load of pollutants.

A comprehensive assessment of hydrochemical indicators is essential to evaluate the current ecological status of surface waters in the Ukrainian section of the Danube. Such analysis forms the basis for understanding pollution dynamics, identifying priority risks, and developing effective environmental management and forecasting strategies in the context of both peace and crisis conditions.

Objects and Research Methods

To assess the ecological state of surface waters and the impact of anthropogenic pressures—including industrial activity, navigation, and military-related factors—on the Danube River, a hydrochemical study was conducted using long-term monitoring data from the Ukrainian section of the river (Reni–Izmail–Vylkove). Data were obtained from the Water Monitoring Laboratory of the Lower Danube Basin Department and included observations collected between 2010 and 2024.

Monitoring focused on key water quality parameters: ammonium, phosphates, sulfate and chloride ions, biochemical oxygen demand over five days (BOD$_5$), and dissolved oxygen. These indicators were analyzed at observation points near the cities of Kiliya and Vylkove, as well as in the river delta, with particular attention to areas of drinking water intake and ecological sensitivity.

The research employed statistical analysis, frequency distribution assessment, and regression modeling to identify trends, determine pollution patterns, and evaluate the river's capacity for self-purification under varying anthropogenic loads. This approach provides a scientific basis for forecasting environmental risks and supporting sustainable water resource management in the Danube basin.

Results and Discussion

1. Physical-Geographical and Hydrological Characteristics of the Danube River Basin

The Danube River is one of the main water arteries of Europe, encompassing the territories of ten countries, including Ukraine. Its lower course, particularly the delta, is located in the southwest of the country and plays an important role in the region's water, ecological, and economic balance. This section is characterized by a complex natural structure, diverse wetland ecosystems, and a high level of biological diversity. The Ukrainian section of the river extends for approximately 174 km and includes a branched delta with numerous arms, lakes, and floodplains. The territory is predominantly flat, with minimal elevation above sea level, which contributes to regular flooding and the formation of marshy landscapes. The Danube Delta is one of the youngest geomorphological formations in Europe and continues to actively change due to sedimentation processes. The climatic conditions of the region are generally moderately continental, with relatively mild winters and hot, dry summers. The level of precipitation is low—within the range of 350–400 mm per year, while evaporation exceeds this value twofold. Such a water deficit affects runoff formation and the ecological state of water bodies. The hydrological regime of the Danube is quite variable and depends on both climatic factors and flow regulation in the upper course. The lower section experiences annual floods lasting from several weeks to several months. Water levels can rise by several meters, influencing the formation of the delta's hydrological cycle and causing changes in the channel network [1].

According to estimates, the average annual water discharge near the city of Kiliya is about 6460 m³/s, but in some years these values may significantly deviate—from historical minimums to extreme maximums. These fluctuations are associated with changes in precipitation, snowmelt in the upper course, as well as economic activities, in particular, the operation of hydraulic structures and land reclamation systems [2].

In addition to natural factors, changes in the Danube's hydrology are intensified by human intervention: engineering restructuring of channels, expansion of navigation routes, deforestation, and draining of wetlands [3]. At the same time, numerical modeling results show that Danube runoff significantly affects water quality and hydrodynamic processes in the adjacent marine area—particularly in the vicinity of Snake Island. This confirms the importance of considering the complex "river–sea" dynamics when assessing the condition of the lower river course [4].

Based on long-term observations of water levels and discharges in the Reni–Izmail section, a general trend of a slight increase in average and maximum levels has been identified, especially pronounced in recent decades. At the same time, seasonal phases—spring floods and autumn low water—remain stable, although peak flow discharges are increasingly shifting to late spring months [5].

2. Hydrochemical Characteristics and Water Quality Assessment of the Danube River

Water quality assessment is a key stage of hydroecological monitoring, especially under conditions of significant anthropogenic pressure. For the Danube River, which is used as a source of drinking water, recreational and industrial needs, the issue of water chemical purity is a priority in terms of sustainable water resource management. The mineralization of water in the Reni–Izmail section has shown a steady decline during the period from 1981 to 2015. This process is associated with an increase in the proportion of fresh meltwater and rainwater in the runoff structure, especially during spring floods. In high-water years, mineralization decreases to 368 mg/dm³, while in low-water periods its level can exceed 425 mg/dm³ [5].

Hydrochemical analysis of water at observation posts in Kiliya and Vylkove indicates regular exceedances of maximum allowable concentrations for parameters such as biochemical oxygen demand (BOD_5), ammonium nitrogen, nitrite nitrogen, as well as chemical oxygen demand (COD). In some months, the Water Pollution Index (WPI) reached 19.35, corresponding to class VII water quality—"extremely polluted water." A positive fact is that the level of dissolved oxygen in water in the summer months was quite high—8.4–9.8 mg/dm³, which facilitated effective natural self-purification of the ecosystem. However, the presence of pollutants such as nitrites, petroleum products, and phenols, even in low concentrations, requires additional control due to their toxicity [6].

One of the most common integral indicators for assessing surface water is the Water Pollution Index (WPI). It allows the combination of various pollution parameters into a single numerical value and assigns the corresponding quality class. The WPI takes into account six main parameters: BOD_5, dissolved oxygen, ammonium, nitrites, petroleum products, and phenols. According to the classification, water with WPI > 10 is considered extremely polluted, and with WPI < 0.3—very clean [7].

In most sources, particularly in the study by Romanchuk M.Ye. and Veslohuzova Z.H., generalized water quality assessment also used integral quality indices based on the average values of several groups of indicators (organoleptic, toxicological, general sanitary). Based on these indices, the water of the Danube River in 2022 in the Kiliya area was classified within the second–third quality classes—"satisfactory," "slightly polluted" [8].

An important problem noted in modern studies is the discrepancy between Ukrainian and European water quality assessment standards. European approaches, which are increasingly being integrated into Ukrainian practice, focus not only on chemical parameters but also on biological and morphological indicators, allowing a comprehensive assessment of the ecological state of water bodies [6].

3. Anthropogenic Impact on the Condition of the Danube River Surface Waters

The lower course of the Danube, flowing through the territory of Ukraine, experiences significant anthropogenic pressure caused by both industrial and agricultural use of water, as well as urban wastewater discharge. This leads to changes in hydrochemical parameters, disturbances of aquatic ecosystems, accumulation of toxic substances, and degradation of the aquatic environment. The reduction of suspended sediment runoff over the past 30 years has been recorded as a result of the construction of hydraulic structures, water intake for irrigation and industrial needs. The most noticeable decline occurred during 1990–2015. This may lead to reduced silting of channels connecting the Danube lakes with the river and, consequently, to improved water exchange quality between them [5].

The main sources of water pollution in the Danube basin are municipal treatment facilities, which are mostly outdated and overloaded. In 2020, municipal sources discharged over 785 tons of organic substances in terms of BOD_5, and nearly 2000 tons in terms of COD. At the same time, the design capacities of treatment facilities were significantly exceeded, which led to the discharge of insufficiently treated or even untreated effluents into the river [6]. An additional threat is posed by food and paper industry enterprises. According to observations, the organic load from these sectors amounted to 9.1 tons for BOD_5 and 98.9 tons for COD, while the contribution from point agricultural sources is relatively minor. Accidental pollution caused by industrial facility malfunctions also poses a separate danger. For example, in 2000, a large volume of wastewater with high cyanide and heavy metal content entered the Danube due to an accident in Romania. Such situations not only disrupt the local state of the waters but also pose a transboundary ecological threat [6].

Prolonged load results in significant changes in the hydrochemical characteristics of water. Harmful compounds such as heavy metals and pesticides accumulate in the delta waters, along with increasing mineralization and changes in pH. All of this threatens aquatic flora and fauna, disrupts biodiversity, and may lead to eutrophication of water bodies [3].

Anthropogenic pressure also alters the river’s morphological structure—dam and canal construction changes flow hydrodynamics, hinders migration of aquatic organisms, and reduces the river’s self-purification capacity [6]. Since 2022, due to armed aggression, the number of potentially environmentally hazardous situations has increased—including the destruction of hydraulic structures, pollution by petroleum products, ammunition, and other toxicants. This is particularly relevant for the southern region of Ukraine, where the Danube Delta is located. Research confirms that the war has not only immediate but also long-term impacts on the hydroecological condition of water bodies [6].

4. The Influence of the Danube River on the Ecosystem of the Black Sea

The Danube is the main source of fresh water for the northwestern shelf of the Black Sea. The river's runoff transports water masses that influence salinity, temperature, and chemical composition of marine water through advection and diffusion processes. In high-water years, the area of Danube runoff distribution covers a significant part of the shelf, substantially altering its hydrodynamic characteristics.

Modeling confirms that the river runoff affects marine waters not only by changing salinity but also by transporting pollutants. In particular, in the coastal zone near Snake Island, reduced water transparency, fluctuations in oxygen content, and increased levels of biogenic elements are observed [4].

As a result of intensive input of nitrogen, phosphorus compounds, and organic matter with river runoff, eutrophication is observed in the northwestern part of the Black Sea. This leads to rapid algal growth, reduced transparency, and oxygen depletion in bottom layers. Hypoxic conditions resulting from algal blooms negatively affect the flora and fauna of the marine zone. In such conditions, oxygen-depleted zones may form, causing mass mortality of aquatic organisms and destabilization of the ecosystem [3].

5. The Importance of the Danube River for Economy and Navigation

The Danube River water is widely used to supply the population with drinking water, especially in Kiliya and Vylkove. However, hydrochemical analysis indicates frequent exceedances of maximum permissible concentrations for BOD_5, nitrites, ammonium, and COD. This threatens the quality of drinking water supply and requires improvement of treatment systems. According to the study, in some years, water from the control site at 48 km was classified as extremely polluted (class VII), indicating a high health risk for consumers [6, 8].

The Danube performs an important transport function as part of the international water corridor. However, intensive navigation leads to several environmental problems: shoreline erosion, wave generation, pollution by petroleum products, and mechanical damage to benthic biocenoses [6].

In addition, port and canal infrastructure (e.g., the Danube–Black Sea Canal) changes current speeds and sediment structure, degrading the condition of aquatic ecosystems in the estuarine zone [3]. Particular attention is drawn to the implementation of the deep-water navigation route "Danube–Black Sea" through the Bystre mouth, which since the early 2000s has been the subject of international discussion. The main goal is to restore navigation in the Ukrainian part of the delta, creating an alternative to the Romanian Sulina Canal. The project is viewed as Ukraine's attempt to strengthen its presence on the Pan-European Transport Corridor VII. At the same time, the construction of the route has faced opposition from Romania and a number of international environmental organizations emphasizing its potential impact on the Danube Biosphere Reserve, part of which is located in the Bystre estuary. Nevertheless, the Ukrainian side insists that the project complies with international standards and considers it technically and logistically advantageous due to its shorter length and economic feasibility [9].

An important institutional mechanism for international navigation regulation on the Danube is the Danube Commission—an intergovernmental organization established under the Belgrade Convention of 1948. Its structure and authority aim to ensure free, safe, and equitable navigation for all Danube countries. In recent years, the commission has undergone significant updates due to the need to adapt to technological progress in navigation, new standards (ES-TRIN, PLATINA 3), and challenges associated with Russia's military aggression. In 2022, the Danube Commission suspended Russia's powers, condemning violations of navigation freedom and the safety of Ukraine's port infrastructure. The Commission plays a coordinating role in standardizing navigation dimensions, hydraulic engineering works, and integrating the Danube into the European TEN-T transport network. Some of its projects (e.g., Green Deal, GRENDEL, RIS COMEX) are aimed not only at improving navigation conditions but also at ensuring the ecological safety of the river environment. This integrated approach makes the commission a key link in the sustainable development of Danube navigation [10].

In order to assess the impact of anthropogenic pressure, including the intensification of navigation and the war, on the condition of surface waters in the Danube River, an analysis was conducted of water quality indicators at the monitoring station: Danube River, 163 km, Reni city, border with Romania (45°46′72″ N, 28°22′95″ E). The data used were obtained from the Water Monitoring Laboratory of the Basin Department for Water Resources of the Black Sea and Lower Danube Rivers. The study focused on the following parameters: phosphate ions, ammonium ions, sulfate ions, chloride ions, biochemical oxygen demand over five days (BOD_5), and dissolved oxygen.

Figure 1 presents the results of the analysis of phosphate and ammonium ion dynamics in the surface waters of the Danube River during the period from 2004 to 2024.

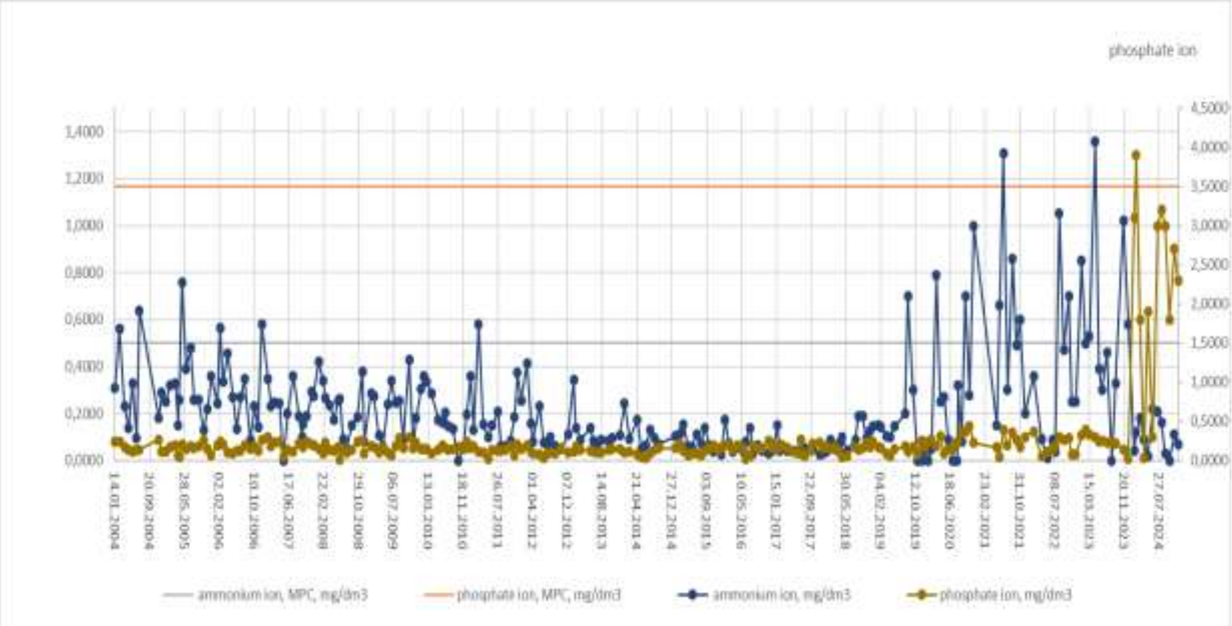

Fig. 1 – Dynamics of Ammonium and Phosphate Ion Concentrations in Aquatic Environment Compared to Maximum Permissible Concentrations (MPC) (2003–2024)

The graph illustrates the long-term dynamics of ammonium (NH_4^+) and phosphate (PO_4^{3-}) ion concentrations in surface waters from 2004 to 2024. A noticeable upward trend in concentrations, especially after 2020, may indicate increased anthropogenic pressure such as discharges of untreated or insufficiently treated wastewater, agricultural runoff, and urban development. The orange and gray lines represent the maximum permissible concentrations (MPCs) for phosphate (1.1 mg/dm³) and ammonium (0.39 mg/dm³), respectively. Frequent exceedances of these limits signal ecological degradation, deterioration of water quality, and heightened risk of eutrophication, posing a threat to aquatic biodiversity.

Figure 2 presents the results of the analysis of the dynamics of sulfate and chloride ion concentrations in the surface waters of the Danube River during the period from 2003 to 2024.

The graph shows the fluctuations in sulfate (SO_4^{2-}) and chloride (Cl^-) ion concen-trations in surface waters from 2003 to 2025. The maximum permissible concentration (MPC) for sulfate is marked with an orange line (100 mg/dm³), while values for chloride appear to reference regulatory thresholds (green). Recur-rent exceedances of sulfate levels, especially in recent years, may reflect increased industrial discharge, mine drainage, or agrochemical runoff. Chloride levels are more stable, but their accumulation can indicate secondary salinization. These chemical shifts in aquatic environments affect aquatic organisms, disrupt ecosystems, and emphasize the need for enhanced environmental monitoring and pollution mitigation strategies.

Figure 3 presents the results of the analysis of the dynamics of dissolved oxygen concentration and five-day biochemical oxygen demand (BOD_5) in the surface waters of the Danube River during the period from 2004 to 2024.

The graph shows the fluctuations of dissolved oxygen (DO, yellow line) and biochemical oxygen demand over 5 days (BOD_5, orange line) in surface waters from 2004 to 2024. The blue line represents the maximum permissible concentration (MPC) for dissolved oxygen (4.0 mgO_2/dm^3), while the gray line marks the BOD_5 threshold (approximately 3.0 mgO_2/dm^3).

Dissolved oxygen is a critical ecological indicator: drops below the MPC can lead to hypoxia and threaten aquatic life. BOD_5 reflects the level of organic pollution — higher values indicate increased oxygen consumption for decomposition. Repeated BOD_5 exceedances along with low oxygen episodes point to anthropogenic pressure such as wastewater discharge and organic contamination, signaling a risk of eutrophication and ecosystem degradation.

For a general assessment of the level of anthropogenic pressure from pollutants and their impact on BOD_5 levels and dissolved oxygen concentration, distribution histograms were constructed for the period 2003–2024.

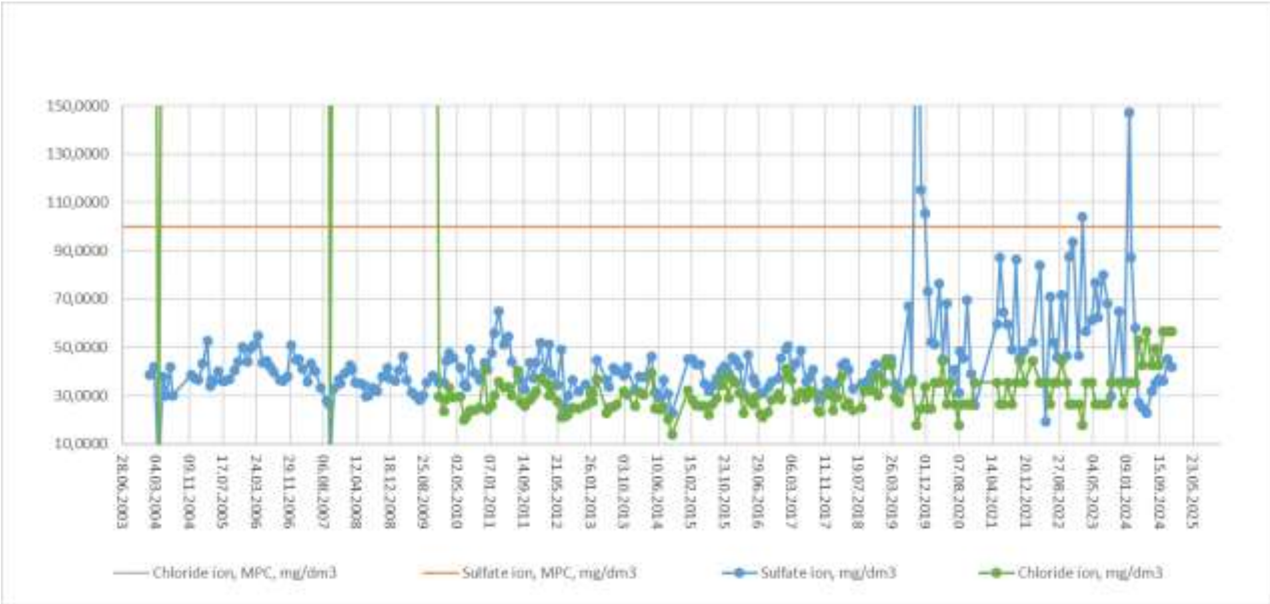

Fig. 2 – Assessment of Chloride and Sulfate Ion Concentration Variability in Surface Waters in the Context of Environmental Safety (2003–2024)

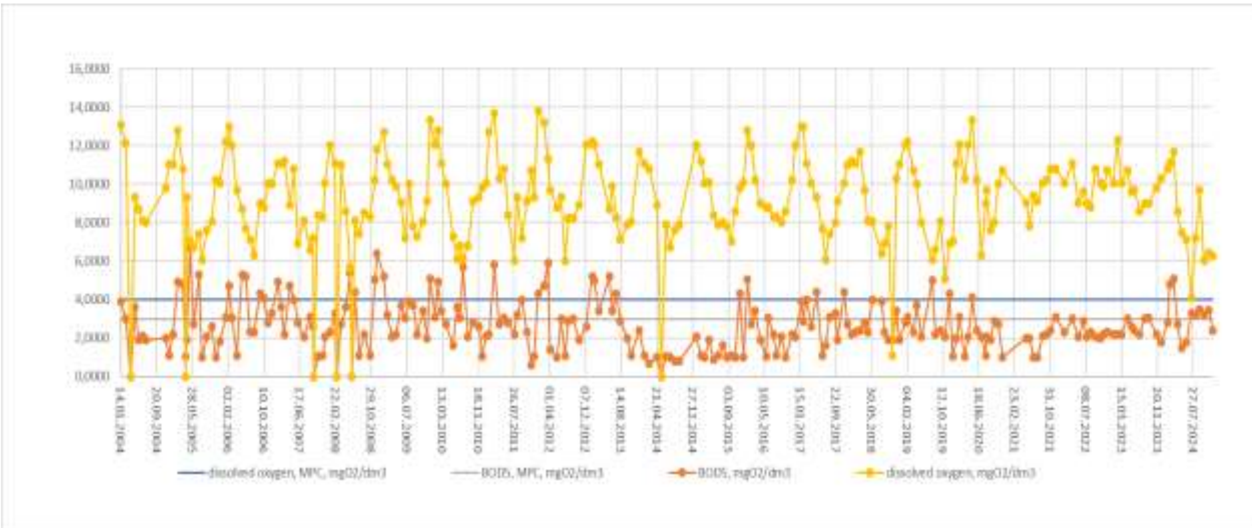

Fig. 3 – Monitoring of Dissolved Oxygen and Biochemical Oxygen Demand (BOD_5) in Aquatic Ecosystems: Indicators of Aeration and Organic Pollution (2004–2024)

Figure 4 presents the histogram of the distribution of phosphate ion concentrations in the surface waters of the Danube River during the period from 2004 to 2024.

The histogram shows the frequency distribution of phosphate (PO_4^{3-}) concentrations in water. The vast majority of samples (over 90%) fall within the 0.1–0.5 mg/dm³ range, indicating a low level of eutrophication pressure. However, a few samples exceed 1.0 mg/dm³, which may point to localized pollution from domestic wastewater, detergents, or fertilizers.

Figure 5 presents the histogram of the distribution of ammonium ion concentrations in the surface waters of the Danube River during the period from 2004 to 2024.

This histogram displays the frequency distribution of ammonium ion (NH_4^+) concentrations in water. Over 80% of the samples show concentrations below 0.5 mg/dm³, indicating generally low pollution levels, typical for waters with limited organic input. However, the presence of samples exceeding 1.0 mg/dm³ may indicate localized

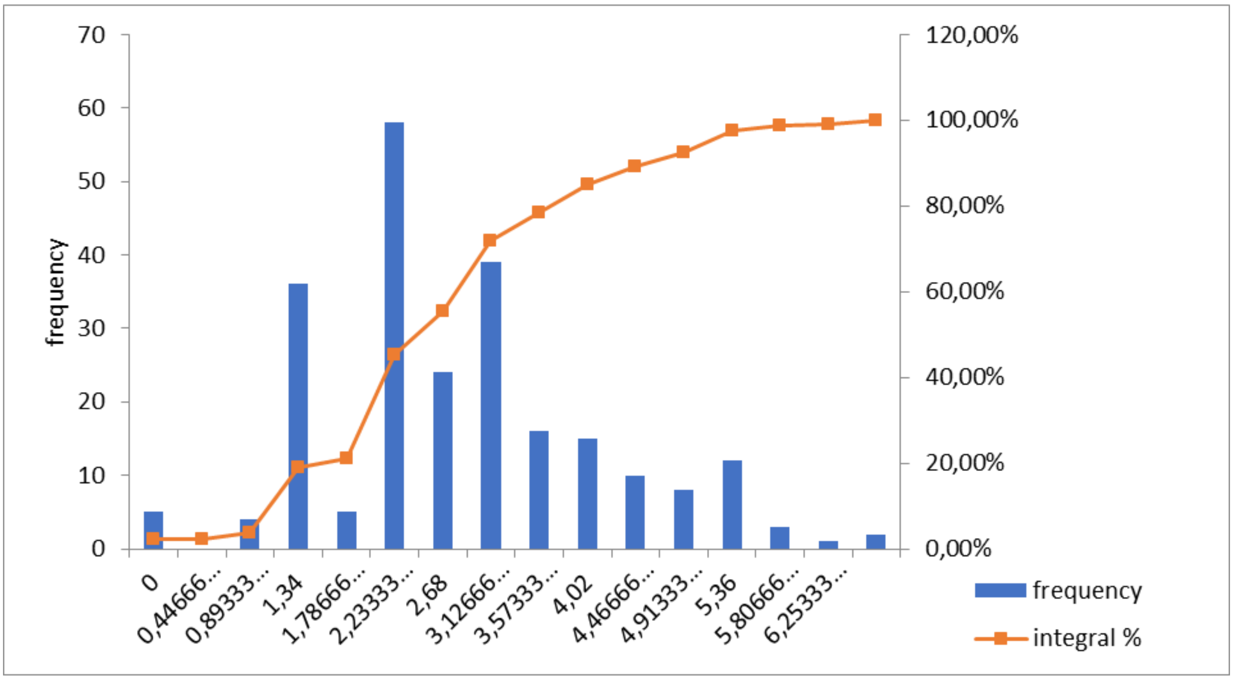

Fig. 4 – Distribution histogram of Phosphate Concentrations in Water with Cumulative Percentage Analysis (2004–2024)

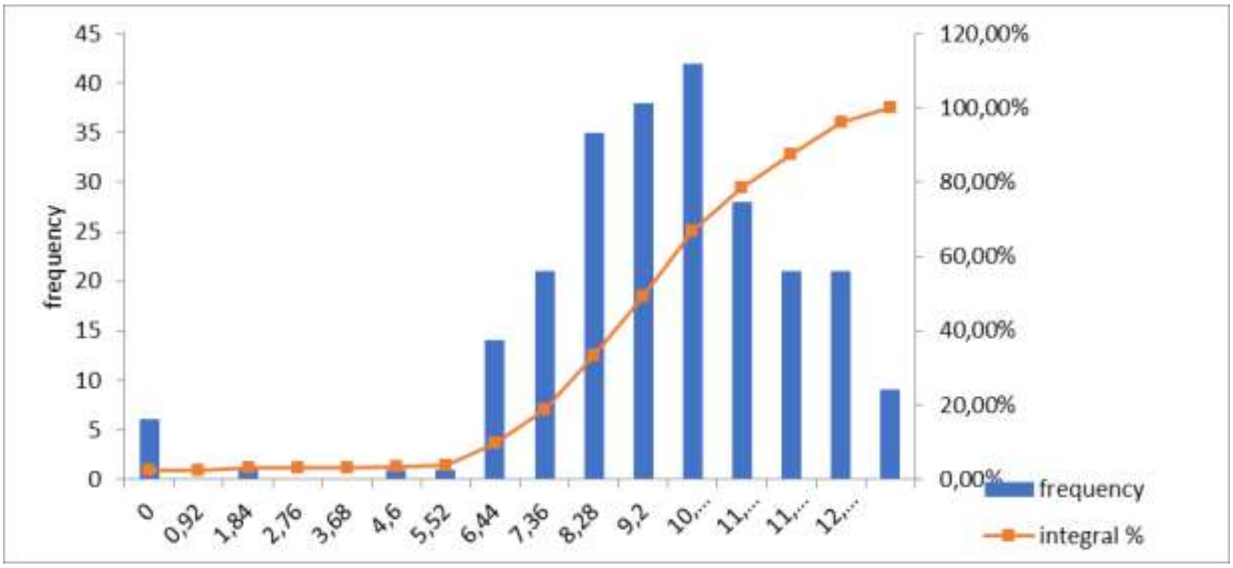

Fig. 5 – Distribution histogram of Ammonium Ion Concentrations in Water with Cumulative Frequency Analysis (2004–2024)

sources of contamination, such as domestic or agricultural wastewater discharges. Ammonium is a sensitive indicator of recent organic pollution, and elevated levels require attention through environmental monitoring.

Figure 6 presents the histogram of the distribution of sulfate ion concentrations in the surface waters of the Danube River during the period from 2004 to 2024.

The distribution of sulfate concentrations shows peaks within the range of 40–60 mg/dm³, which corresponds to the natural level of mineralization for large river systems experiencing moderate anthropogenic pressure. The majority of values (over 80%) are concentrated within the 45–50 mg/dm³ range. This indicates a stable source of sulfate input — particularly from natural minerals (such as gypsum and sulfides), as well as

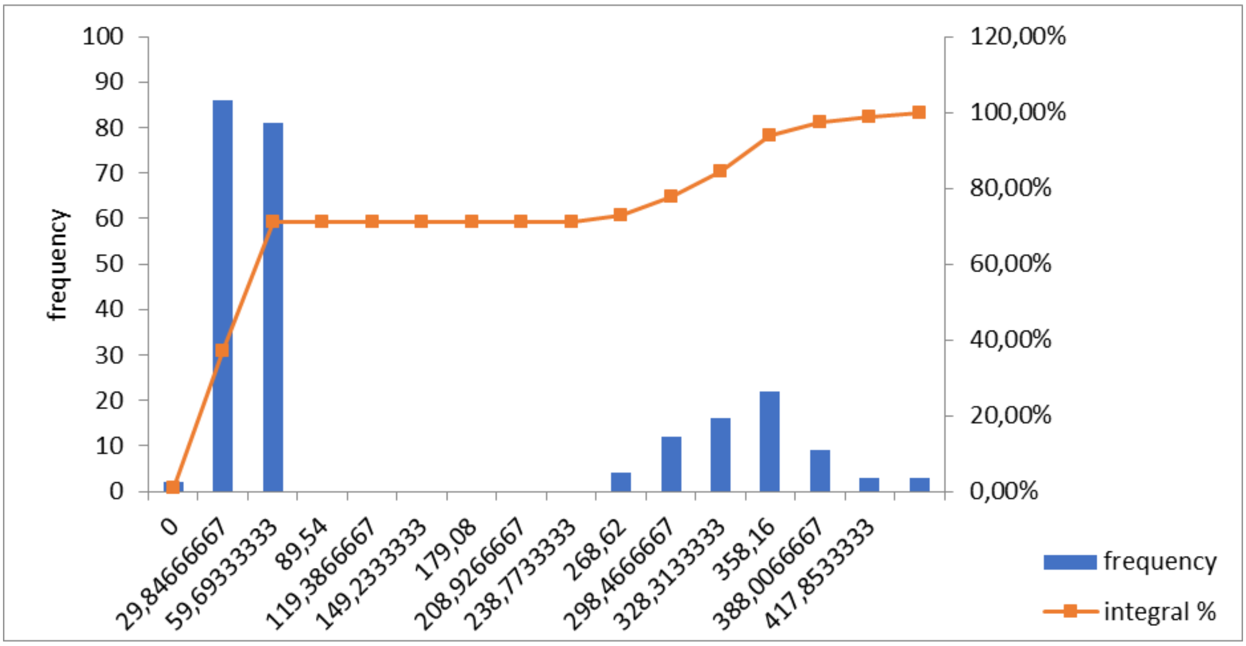

Fig. 6 – Distribution histogram of Sulfate Concentrations in the Aquatic Environment with Cumulative Frequency Analysis (2004–2024)

from domestic and industrial wastewater. Isolated instances of higher concentrations may result from localized pollution, desorption processes from bottom sediments, or the influence of atmospheric runoff. Such a distribution profile is typical for river systems subject to seasonal variability and influenced by both natural and anthropogenic sources of SO_4^{2-}. High concentrations in combination with low oxygen levels may also provide a substrate for sulfate reduction with the formation of hydrogen sulfide (H_2S), which is potentially toxic to aquatic biota.

Figure 7 presents the histogram of the distribution of chloride ion concentrations in the surface waters of the Danube River during the period 2004–2024.

The histogram illustrates the frequency distribution of chloride concentrations in the water. As shown, the frequency distribution of chloride pollution levels is heterogeneous. The majority of samples (over 80%) have concentrations up to 90 mg/dm³, indicating a relatively low level of chloride pollution. However, the right side of the chart shows a smaller but noticeable number of samples with concentrations exceeding 200 mg/dm³. Data on chloride ion concentrations indicate that prior to 2010, the level of chloride pollution was significantly higher and substantially decreased after 2010. Thus, in the context of chloride ion concentration frequencies, it is appropriate to conduct a separate analysis starting from 2010. The results of this analysis are presented in Figure 8.

The histogram shows the frequency distribution of chloride ion (Cl^-) concentrations in water. The majority of samples (over 80%) fall within the 25–45 mg/dm³ range, indicating a moderate and stable level of mineralization, typical for natural freshwater systems. However, a few values exceed 50 mg/dm³, suggesting possible local sources of elevated chloride input, such as municipal or industrial discharges, road de-icing agents, or soil salinization.Elevated chloride levels can adversely affect aquatic ecosystems by disrupting the osmotic balance of organisms, reducing biodiversity, and degrading drinking water quality.

A comparison of the two histograms indicates that since 2010, the level of chloride pollution in the surface waters of the Danube has decreased. This is most likely associated with a reduction in anthropogenic pressure due to decreased use of inorganic fertilizers, such as potassium chloride, and improvements in the quality of municipal wastewater.

Figure 9 presents the histogram of the distribution of BOD_5 values in the surface waters of the Danube River over the period 2004–2024.

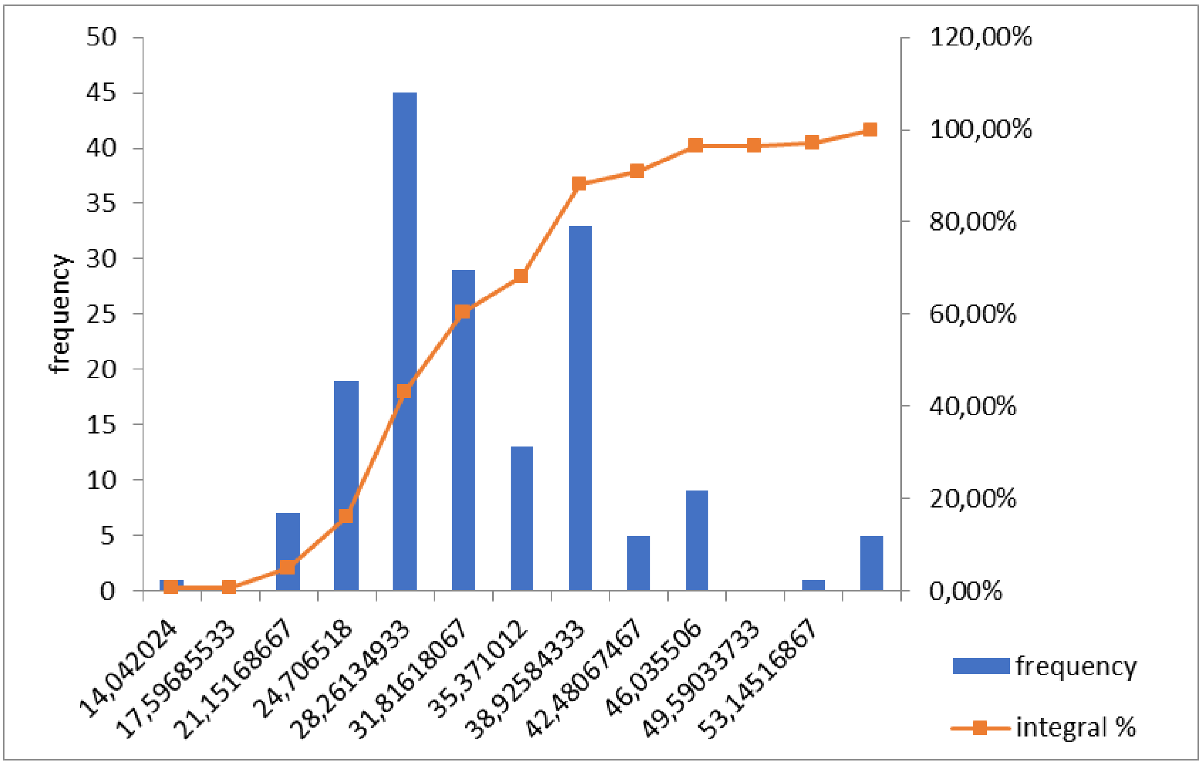

Fig. 7 – Distribution histogram of Chloride Ion Concentrations in Water with Cumulative Percentage Assessment (2004 – 2024)

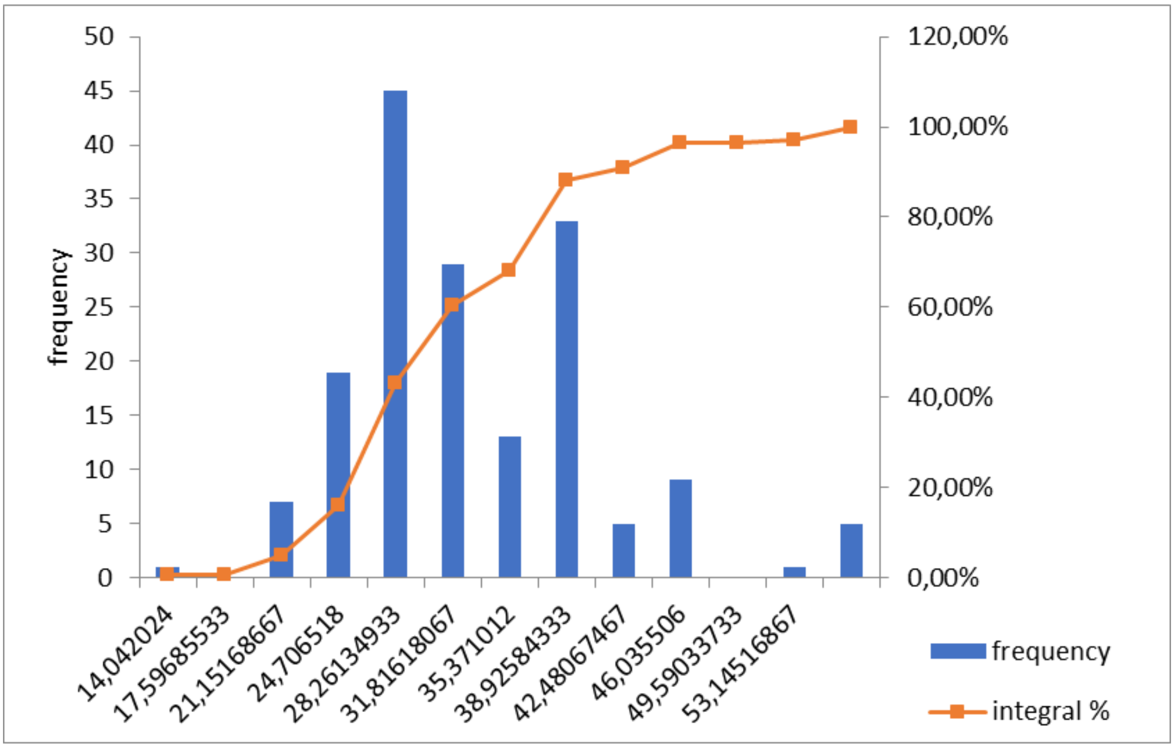

Fig. 8 – Distribution histogram of Chloride Ion Concentrations in Water with Cumulative Percentage Assessment (2010 – 2024)

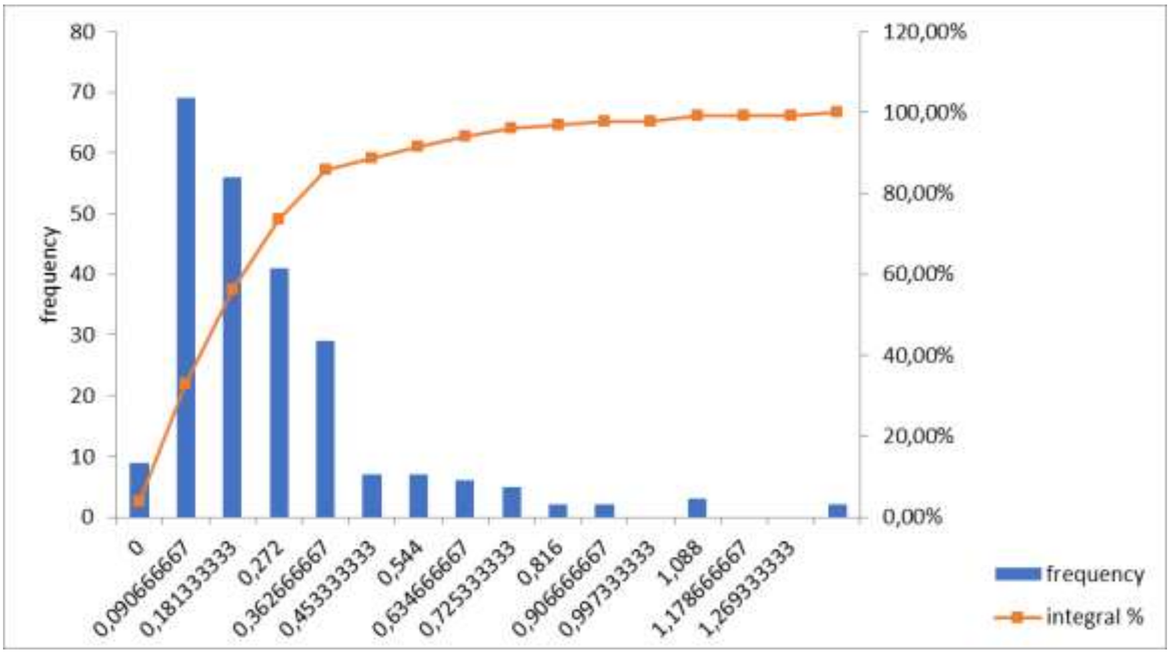

Fig. 9 – Distribution histogram of BOD_5 values and cumulative percentage: assessment of organic pollution in aquatic environments (2004 – 2024)

This histogram shows the distribution of BOD_5 (Biochemical Oxygen Demand over 5 days), an indicator of organic pollution in water. Most samples fall within the 2.2–2.7 mgO_2/dm^3 range, indicating moderate contamination. However, about 20% of values exceed 4.0 mgO_2/dm^3 — the threshold where negative effects on aquatic organisms can occur. This suggests the presence of organic pollution sources that may lead to decreased dissolved oxygen, eutrophication, and overall deterioration of the water body's ecological condition.

Figure 10 presents the histogram of the distribution of dissolved oxygen concentrations in the surface waters of the Danube River over the period 2004–2024.

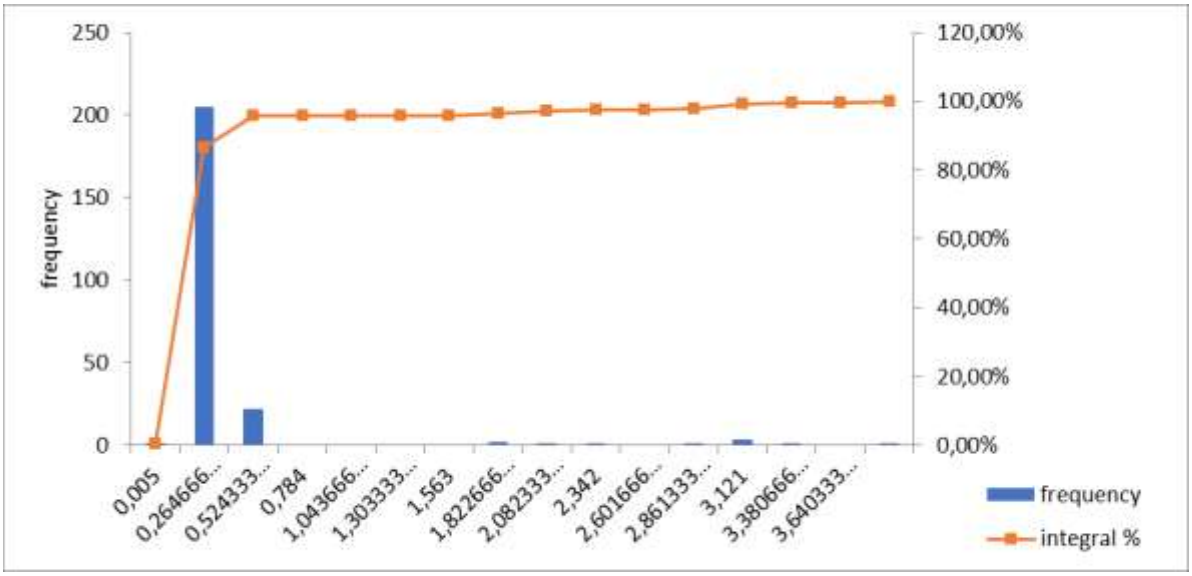

Fig. 10 – Distribution histogram of Dissolved Oxygen Concentrations in Water and Cumulative Sample Percentage (2004 – 2024)

This histogram shows the frequency distribution of dissolved oxygen levels in the aquatic environment. Most samples fall within the 9–11 mgO_2/dm^3 range, indicating a well-oxygenated ecosystem that supports aquatic life. Approximately 90% of the samples exceed 7 mgO_2/dm^3, suggesting a stable ecological condition of the water body. Lower oxygen values are rare but should be monitored to prevent hypoxia and associated risks to biodiversity.

In order to determine the dynamics of changes in the level of anthropogenic pressure on the surface waters of the Danube River (Reni station) and to further forecast in the context of specific pollutants, appropriate regression equations were constructed.Annual average values of harmful substance discharges were used in their construction (thus smoothing the seasonality of pollution).

Figure 11 shows the dynamics of changes in phosphate and ammonium ion concentrations in the water during 2004–2024, along with the corresponding approximating curves.

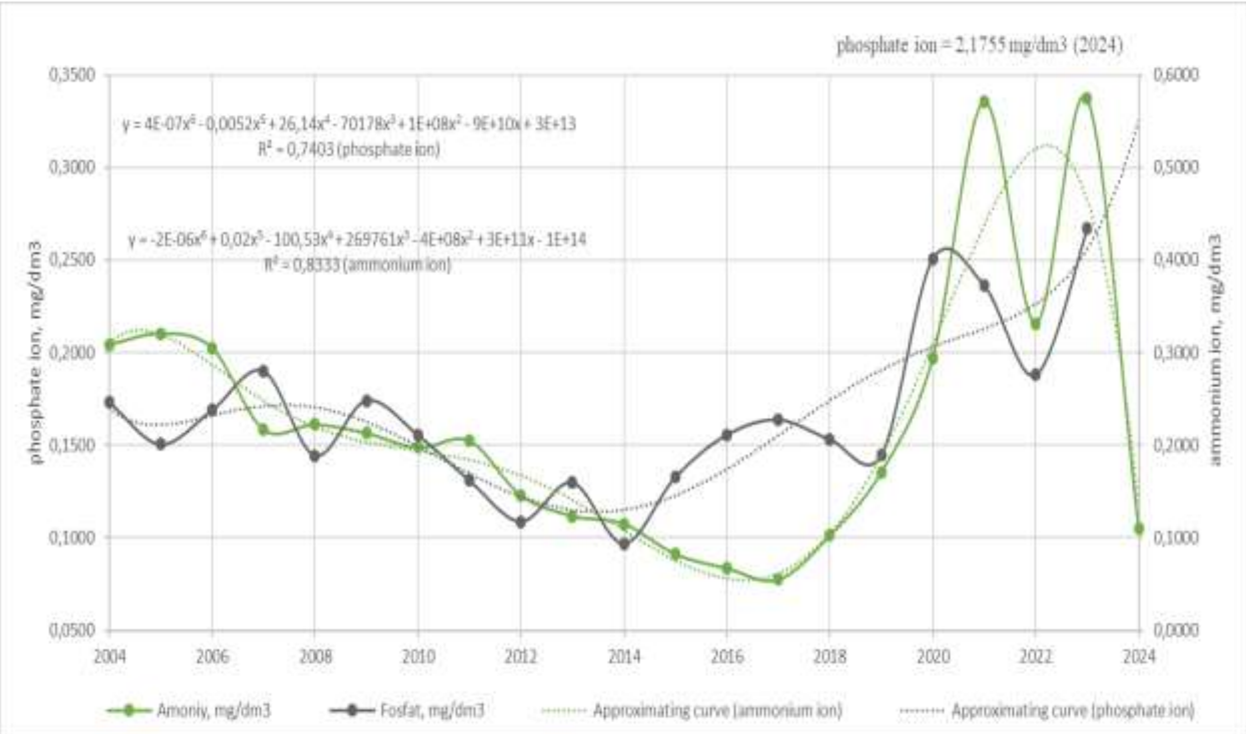

Fig. 11 – Dynamics of phosphate and ammonium ion concentrations in water from 2004 to 2024 and the corresponding approximating curves (2004-2024)

The regression equation of the identified dependence for phosphate ions is:

$$y = 4 \times 10^{-7}x^6 - 5.2 \times 10^3x^5 + 26.14x^4 - 7.0178 \times 10^4x^3 + 1 \times 10^8x^2 - 9 \times 10^{10}x + 3 \times 10^{13},$$

approximation reliability – $R^2 = 0.7403$.

The identified dependencies indicate that a decrease in phosphate ion content in the water is observed periodically, but starting from 2014 the overall level began to increase. When constructing the regression equation, the data for 2024 were not taken into account because they significantly differ from previous years (the average value of the indicator increased to 2.1755 mg/dm^3).

The regression equation of the identified dependence for ammonium ions is:

$$y = -2 \times 10^{-6}x^6 + 0.02 \times 10^2x^5 - 100.53x^4 + 2.69761 \times 10^5x^3 - 4 \times 10^8x^2 + 3 \times 10^{11}x - 1 \times 10^{14},$$

approximation reliability – $R^2 = 0.8333$.

The identified dependencies indicate that a decrease in ammonium ion content in water is also observed periodically with a general downward trend. However, starting from 2017, the indicators began to rise sharply and significantly decreased to the previous level only in 2024.

Figure 12 presents the dynamics of changes in sulfate and chloride ion concentrations in water from 2013 to 2024 and the corresponding approximating curves.

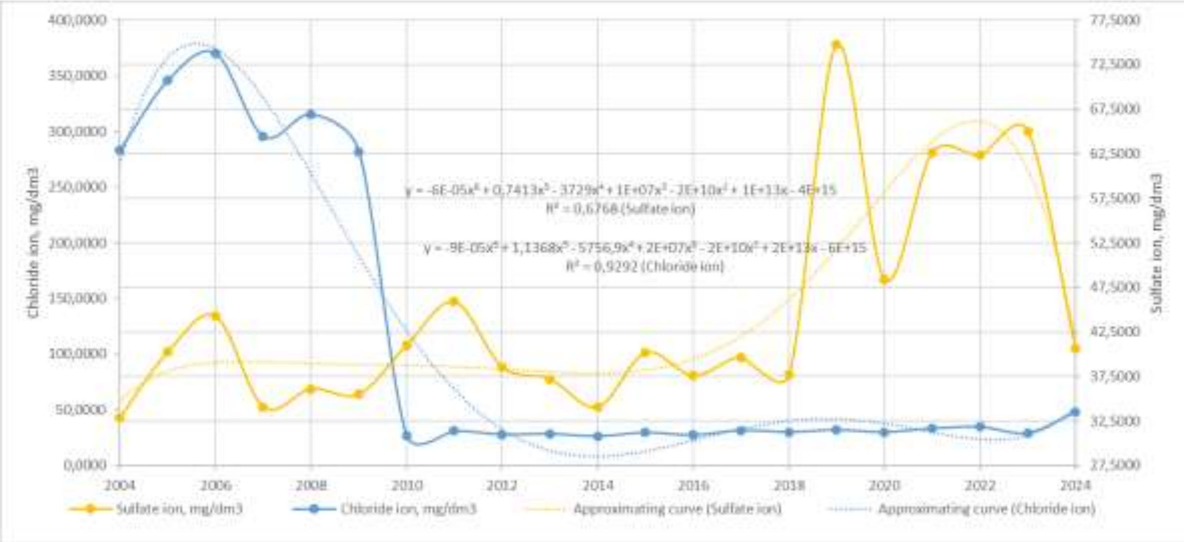

Fig. 12 – Dynamics of sulfate and chloride ion concentrations in water from 2004 to 2024 and the corresponding approximating curves (2013-2024)

The regression equation of the identified dependence for sulfate ions is:

$y = -6 \times 10^{-5}x^6 + 0.7413x^5 + 1 \times 10^7x^4 - 3.729 \times 10^3x^3 + 1 \times 10^7x^2 + 1 \times 10^{13}x - 6 \times 10^{15}$, approximation reliability – $R^2 = 0.6768$.

The regression equation of the identified dependence for chloride ions is:

$y = -9 \times 10^{-5}x^6 + 1.1368x^5 - 5.75569x^4 + 2 \times 10^7x^3 - 2 \times 10^{13}x^2 + 2 \times 10^{13}x - 6 \times 10^{15}$, approximation reliability – $R^2 = 0.794$. The identified dependencies indicate that the changes in the content of chloride ions in water are also relatively minor. As observed, the content of sulfate ions from 2004 to 2018 fluctuated around the average level, increased significantly during 2019–2023, and decreased again in 2024. Regarding chloride ions, their content was high until 2010. However, starting from 2011, it significantly decreased and only increased again in 2024.

Therefore, we conducted an additional analysis of the situation from 2010 to 2024 to refine the regression equation. Figure 13 presents the dynamics of changes in the concentrations of sulfate and chloride ions in the water during the period 2010–2024, along with the corresponding approximating curves.

Fig. 13 – Dynamics of sulfate and chloride ion concentrations in water from 2010 to 2024 and the corresponding approximating curves (2010-2024)

The regression equation of the identified dependence for sulfate ions is:

$y = 2 \times 10^{-4}x^6 - 2.7202x^5 + 1.3705 \times 10^4x^4 - 4 \times 10^7x^3 + 6 \times 10^{10}x^2 - 4 \times 10^{13}x + 2 \times 10^{16}$,

with an approximation reliability of $R^2 = 0.832$.

The regression equation of the identified dependence for chloride ions is:

$y = -6 \times 10^{-5}x^6 + 0.7413x^5 - 3.729 \times 10^4x^4 + 1 \times 10^7x^3 - 2 \times 10^{10}x^2 + 1 \times 10^{13}x - 4 \times 10^{15}$,

with an approximation reliability of $R^2 = 0.6768$.

Figure 14 presents the dynamics of changes in BOD_5 (Biochemical Oxygen Demand over 5 days) and dissolved oxygen concentrations during the period 2013–2024, along with the corresponding approximating curves.

The identified dependencies show that the lowest levels of this indicator were recorded in 2014 and 2024. Thus, there are opposite trends for BOD_5 and dissolved oxygen, as expected. The obtained results support the assumption of the presence of a self-purification capacity despite existing anthropogenic impacts.

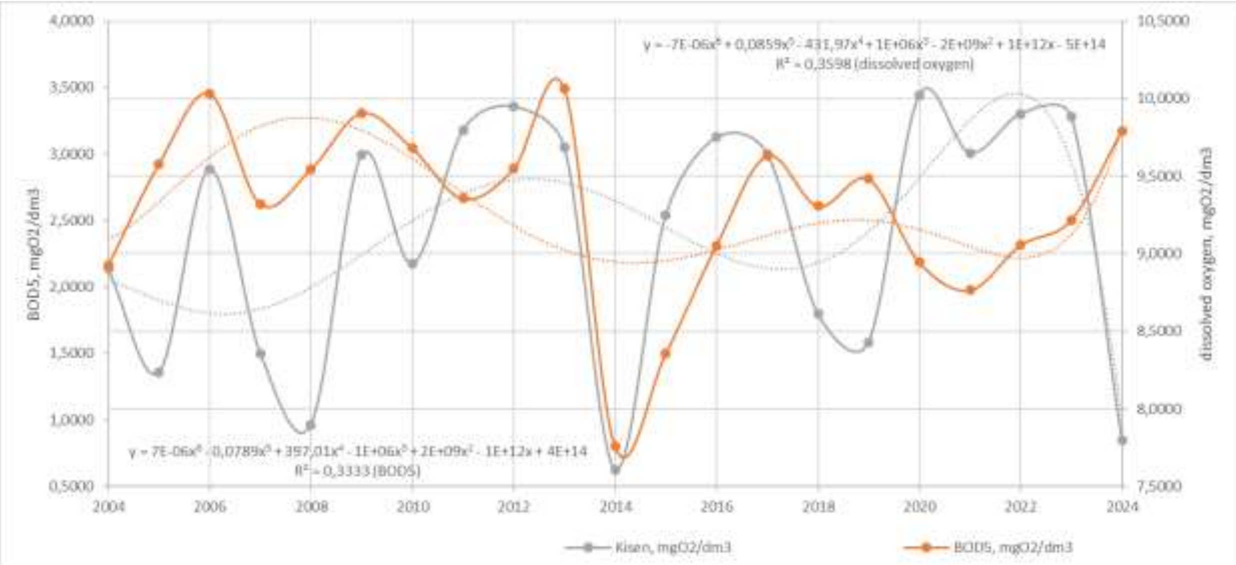

Fig. 14 – Dynamics of BOD_5 and dissolved oxygen concentrations in water from 2013 to 2024 and the corresponding approximating curves (2013-2024)

Conclusions

This study conducted an analysis of the impact of anthropogenic pressure on the state of surface waters in the Danube River. The research covered the period from 2004 to 2024, with a focus on six key water quality indicators: phosphates, ammonium, sulfates, chlorides, biochemical oxygen demand over five days (BOD_5), and dissolved oxygen concentration.

It was established that phosphate and ammonium compounds exhibit seasonal fluctuations due to organic and agricultural discharges. Sulfate concentrations show high variability, influenced by both natural and anthropogenic sources, while chloride levels remain stable, indicating chronic exposure.

The analysis of BOD_5 and dissolved oxygen indicates a potential for self-purification, although episodes of oxygen depletion were recorded, particularly during periods of local organic overloading and disrupted hydrodynamics.

Developed regression models allowed for the identification of correlations between changes in water circulation, the intensity of port activity, and pollution levels.

The main environmental issues of the lower Danube were identified: organic and mineral pollution, eutrophication, oxygen regime deterioration, hydromorphological alterations, and threats posed by armed conflict. Despite these challenges, the river retains a capacity for partial self-recovery, especially under reduced anthropogenic pressure.

Restoration of ecological balance requires the implementation of systematic monitoring, modernization of treatment facilities, effective management of pollution sources, and Ukraine's active participation in international environmental regulatory mechanisms such as the Danube Commission. The modeling results can be used to forecast the state of the aquatic environment in both peacetime and post-war recovery scenarios.

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Conflict of Interest

The author declares no conflict of interest regarding the publication of this manuscript. Furthermore, the author has fully adhered to ethical norms, including avoiding plagiarism, data falsification, and duplicate publication.

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ЕКОЛОГІЧНА ОЦІНКА СТАНУ ПОВЕРХНЕВИХ ВОД РІЧКИ ДУНАЙ

Мета. Надати комплексну екологічну оцінку та здійснити прогнозування стану поверхневих вод річки Дунай у межах української ділянки (Рені – Ізмаїл – Вилкове) з акцентом на динаміку основних гідрохімічних показників за період 2010–2024 років. Особлива увага приділяється впливу антропогенних чинників, зокрема інтенсивному судноплавству, промисловому навантаженню та екологічним наслідкам воєнних дій, які змінили гідрологічний режим та погіршили якість водного середовища.

Методи. Системний аналіз, методи статистичної обробки, аналіз розподілу та побудова регресійних моделей використані для оцінки ретроспективної динаміки та прогнозування майбутніх тенденцій у якості вод. Джерелом інформації слугували дані довготривалого моніторингу, зібрані на постах у м. Кілія, м. Вилкове та в гирловій частині річки.

Результати. Основна увага зосереджена на шести ключових показниках якості води: фосфати, амоній, сульфати, хлориди, біохімічне споживання кисню протягом п'яти діб (БСК$_5$) та концентрація розчиненого кисню. Встановлено, що фосфатні та амонійні сполуки демонструють сезонні коливання, зумовлені скидами органічного та аграрного походження. Концентрація сульфатів характеризується свідчить високою мінливістю, яка поєднує природні та антропогенні джерела, тоді як хлориди залишаються стабільними, з ознаками хронічного впливу. Аналіз показників БСК$_5$ та розчиненого кисню свідчить про потенціал до самоочищення, хоча в окремі періоди фіксується погіршення кисневого балансу, зокрема внаслідок локального перевантаження органікою та порушення гідродинамічного режиму. Розроблені регресійні моделі дозволили встановити зв'язки між змінами у водообігу, інтенсивністю портової діяльності та забрудненням.

Висновки. Встановлено основні екологічні проблеми нижньої течії річки Дунай: органічне та мінеральне забруднення, евтрофікація, зниження кисневого режиму, гідроморфологічні зміни, а також загрози від збройного конфлікту. Попри це, річка зберігає здатність до часткового самовідновлення, особливо за умов зниження антропогенного навантаження. Відновлення екологічної рівноваги потребує впровадження системного моніторингу, модернізації очисних споруд, управління джерелами забруднення та активної участі України в міжнародних механізмах екологічного регулювання, таких як Дунайська комісія. Результати моделювання можуть бути використані для прогнозування стану водного середовища в умовах як мирного розвитку, так і повоєнного відновлення.

КЛЮЧОВІ СЛОВА: *річка Дунай, поверхневі води, екологічний моніторинг, фосфати, амоній, сульфати, хлориди, розчинений кисень, $БСК_5$, антропогенний вплив, прогнозування, війна*

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