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# Ecological assessment and forecasting of surface water conditions in the Southern Bug River in the territory of Mykolaiv region

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**ABSTRACT**

**Introduction.** The issue of water supply and water security has become more relevant in the territory of Ukraine under conditions of war. Taking into account that Ukraine has an extensive water infrastructure, which includes large multipurpose reservoirs, hydroelectric power station dams, cooling systems for nuclear power plants, and others, the impact of the war is already environmentally hazardous and catastrophic. That is why research into anthropogenic influence, including during military actions, is relevant for the Southern Bug River, which is an important strategic resource for the ecological, social, and economic development of the Mykolaiv region of Ukraine.

**The purpose of article.** Assessment of anthropogenic and military impact on the surface waters of the Southern Bug River within the Mykolaiv region, which are used for drinking water supply, in order to forecast the development of the ecological situation and to form measures for its improvement at the stage of post-war recovery of the country.

**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.** The paper presents the results of studies on the impact of anthropogenic and military pressure on the ecological state of surface waters within the Mykolaiv region, namely the Southern Bug River, at 153 km, near the village of Oleksiivka (village of Pankratove), drinking water intake of the city of Yuzhnoukrainsk, Mykolaiv region (47°86′87″ N, 31°11′97″ E). A forecast of the level of anthropogenic load from key pollutants was carried out using regression equations, and projected levels of phosphate ions, ammonium ions, sulfate ions, chloride ions, $BOD_5$, and dissolved oxygen in the surface waters of the Southern Bug River were determined.

**Conclusions.** The study presents the results of a comprehensive ecological assessment of the quality of surface waters of the Southern Bug River in the city of Yuzhnoukrainsk, Mykolaiv region, over the period of 2003–2024. The dynamics of key water quality indicators were studied, in particular the content of phosphate ions, ammonium, sulfate ions, chloride ions, biochemical oxygen demand ($BOD_5$), and the level of dissolved oxygen. The obtained analysis results allow us to conclude that the aquatic system of the Southern Bug River in the area of Oleksiivka (Pankratove) has a stable biogenic-organic load, which intensified during 2020–2024. An increase in nitrogen, phosphates, surfactants, and herbicides indicates a systematic influence of domestic and agricultural pollution sources. The trends in COD/$BOD_5$, combined with a decrease in dissolved oxygen, indicate a decline in aeration potential and an increased risk of hypoxia. A forecast of the anthropogenic load level from key pollutants was carried out using regression equations, and projected levels of phosphate ions, ammonium ions, sulfate ions, chloride ions, $BOD_5$, and dissolved oxygen in the surface waters of the Southern Bug River were determined.

***Keywords****: surface waters, ecological assessment, anthropogenic load, water pollution, correlation data analysis, regression analysis, forecasting.*

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**Introduction.** In Ukraine's water supply system, surface waters play an important role, accounting for approximately 80% of the demand. However, at the same time, the country is among those with limited reserves of freshwater. The problem of water scarcity is particularly acute in the south, especially in the Mykolaiv region. In terms of specific water reserves per area and per capita, the region is among the least provided for among all regions of the country.

The issues of water supply and water security have become more urgent in Ukraine under wartime conditions. Considering that Ukraine has an extensive water infrastructure, which includes large multipurpose reservoirs, hydroelectric power station dams, cooling systems for nuclear power plants, etc., the impact of the war is already environmentally hazardous and catastrophic. In addition, during military aggression, surface and groundwater, as well as atmospheric air, are subjected to direct military influence. This impact is noticeable for major rivers such as the Dnipro, Southern Bug, Inhul, Siverskyi Donets, and Danube, as well as for smaller rivers, natural and artificial reservoirs, and coastal areas of the Azov and Black Seas [1–20].

The results of recent studies on surface waters in different countries are presented in articles [21–23].

Therefore, the study of anthropogenic influence, including during military actions, is especially relevant for the Southern Bug River, which is a vital strategic resource for the ecological, social, and economic development of the Mykolaiv region of Ukraine.

**The aim of this study.** The main source of water supply for most settlements in the Mykolaiv region is surface water, particularly the Southern Bug, Syniukha, and Inhul rivers. In rural areas and district centers, however, underground aquifers are more commonly used.

The rivers within the Southern Bug basin are actively used to meet the needs of industry and the agricultural sector, and they also serve as a source for the replenishment of underground water reserves and play an important role in maintaining the natural ecosystems of the region.

Despite the fact that the ecological state of the Southern Bug basin has already been the subject of scientific research in various fields [1–16], the issues of monitoring and analyzing the quality of surface waters in this area remain extremely relevant.

Therefore, the main objective of the conducted study was to assess the anthropogenic and military impact on the surface waters of the Southern Bug River within the Mykolaiv region, which are used for the drinking water supply of the city of Yuzhnoukrainsk, in order to forecast the development of the ecological situation and to formulate measures for its improvement during the post-war recovery of the country.

**Research methods.** The study was conducted based on data from the Laboratory of Water and Soil Monitoring of the Regional Office of Water Resources (ROVR) in the Mykolaiv region and covered the period from 2003 to 2024 in the context of the following indicators: phosphate ions, ammonium ions, sulfate ions, chloride ions, $BOD_5$, 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 basin of the Southern Bug River is considered one of the oldest drainage areas on the territory of Ukraine. Its formation is closely linked to tectonic processes that occurred within the Ukrainian Shield – one of the key structural elements of the East European Platform. The geological foundation of the basin is represented by massive formations of crystalline rocks of Archean and Proterozoic age, whose age ranges from 2.5 to 3.0 billion years. The foundation consists of granites, gneisses, quartzites, and amphibolites, which have a complex block structure with pronounced fracturing [1, 2].

In the middle section of the river – from Haivoron to Pervomaisk – ancient crystalline rocks are exposed, forming unique granite rapids. This region, known as the «Buzkyi Gard», has exceptional geomorphological and environmental significance and represents an interaction between tectonic movements and contemporary erosional-accumulative processes [3, 4].

In terms of relief, the basin is structurally complex, encompassing territories of three geographical zones: the Volhynian-Podolian and Dnipro Uplands, as well as the Black Sea Lowland. In the upper reaches of the Southern Bug, deep valleys with a dense network of gullies and ravines developed on loess soils are formed. The middle course is characterized by rocky outcrops of magmatic rocks that form canyons, waterfalls, and rapids. The lower part of the river has wide, weakly incised valleys with alluvial and deluvial deposits, where floodplains, oxbow lakes, deltas, and limans are formed [2].

Tectonic uplifts and subsidences were key factors in the development of the basin, altering the erosion base and contributing to the formation of numerous tributaries, gullies, and ravines. This led to the uneven development of the Southern Bug's valley network. In the lower course, the Pliocene and Pleistocene transgressions of the Black Sea had a significant impact, resulting in the accumulation of thick layers of marine sediments – clays, sandy loams, sands with shell fragments. These deposits are highly permeable and influence the hydrogeochemical regime [2].

The chemical properties of the water are determined by the geological foundation. The water of the Southern Bug is predominantly of hydrocarbonate-calcium composition. This is due to the dissolution of carbonate rocks and secondary salinization of alluvial layers. In the middle and lower courses, mineralization can reach 600–1000 mg/dm³, which significantly affects both aquatic biota and the suitability of water for technical use. Fracturing of the crystalline rocks ensures stable underground inflow to the river during low-water periods, supporting the base flow [6].

Paleogeographic research indicates that the geological structure of the area significantly influenced the settlement of the basin even in prehistoric times. As early as the Mesolithic, the river served as an important transport artery, source of water, and food resources for early communities. Numerous archaeological sites have been discovered near the cities of Pervomaisk, Voznesensk, and Mykolaiv, attesting to continuous human occupation of this region [2].

In recent decades, anthropogenic pressure on the Southern Bug basin has intensified, associated with the development of cities, industrial facilities, agriculture, and a decline in the effectiveness of environmental control. The main sources of pollution include industrial effluents, domestic wastewater, urban stormwater runoff, and agrochemicals – nitrates, phosphates, pesticides, and herbicides washed off from fields [7,8].

The most polluted areas are zones around Khmelnytskyi, Vinnytsia, Pervomaisk, Voznesensk, and Mykolaiv, where the river flows into the Buh Estuary. High concentrations of heavy metals (Cu, Zn, Pb, Ni, Cd), petroleum products, phenols, and surfactants are recorded in the water. This negatively affects benthic ecosystems and the overall ecological condition of the river. Thanks to geoinformation analysis, ecological risk maps have been created [9].

A separate threat is eutrophication, which arises due to excessive input of phosphorus and nitrogen, causing rapid development of blue-green algae. The most vulnerable is the middle course in the Podillia region, where more than 70% of land is used for agriculture. Eutrophication leads to oxygen depletion, reduced water transparency, and decreased biodiversity [10, 11].

An increase in the content of phosphates, nitrites, organic matter, and ammonium is observed in the water, causing the ecosystem to shift into a stable eutrophic or hypertrophic state. At the same time, the composition of the ichthyofauna changes – valuable fish species are displaced by less demanding or invasive ones. The number of mollusks and zooplankton decreases, disrupting food chains [8].

Additional harm is caused by thousands of small water bodies – over 3,500 ponds, reservoirs, and dams – that slow down the flow, reduce aeration, and contribute to the formation of anaerobic zones. Under such conditions, toxic compounds such as methane and hydrogen sulfide are formed, which further deteriorate the state of the aquatic environment.

The Southern Bug is the second-longest river located entirely within Ukraine. Its basin covers an area of over 64,000 km² and includes seven regions, with a population of about 3 million people. The total length of its tributaries exceeds 13,000 km; the largest among them are the Buzhok, Ikva, Syniukha, and Chychykliia [12].

The seasonal dynamics of water flow are clearly expressed: in spring (March–April), during snowmelt, up to 60% of the annual runoff is formed. In summer and autumn, water levels decrease due to lack of precipitation, increased evaporation, and active water abstraction. In dry years, the average discharge in the lower reaches can drop to 60–70 m³/s [13].

Over 3,000 artificial water bodies operate in the basin territory, significantly altering the natural distribution of water, affecting temperature, aeration, and self-purification processes. This disrupts fish migration, reduces the productivity of floodplain zones, and changes the hydrological regime [14].

In the Mykolaiv region, water withdrawal during the summer period reaches 8–10 million m³, while only up to 20% is returned. This causes runoff deficits, drying of small tributaries, and degradation of the coastal ecosystem [13].

Water quality remains problematic. Exceedances of ammonium nitrogen, phosphates, and $BOD_5$ levels are frequently recorded. In the lower course, especially near the estuary, mineralization reaches 800–1000 mg/dm³, making it difficult to use for drinking purposes [15].

Compliance with the EU Water Framework Directive is a current task. The existing monitoring system is mostly focused on chemical indicators, while bioindication is rarely applied. This hinders an adequate assessment of the state of water bodies [11].

Under conditions of climate change, prolonged drought periods, and the risk of desertification in certain regions, it is necessary to implement integrated water resource management: modernization of treatment facilities, ecological restoration of rivers, creation of buffer zones, and optimization of water abstraction regimes [15].

***Research results.*** In order to achieve the stated objective, an analysis of the chemical composition of water was conducted at the drinking water intake site in the city of Yuzhnoukrainsk, Mykolaiv region: the Southern Bug River, 153 km mark, near the village of Oleksiivka (village of Pankratove), (47°86′87″ N, 31°11′97″ E) (Fig. 1).

The catchment basin of the Southern Bug River has a shape close to pear-shaped but with irregular contours. From a tectonic perspective, the majority of

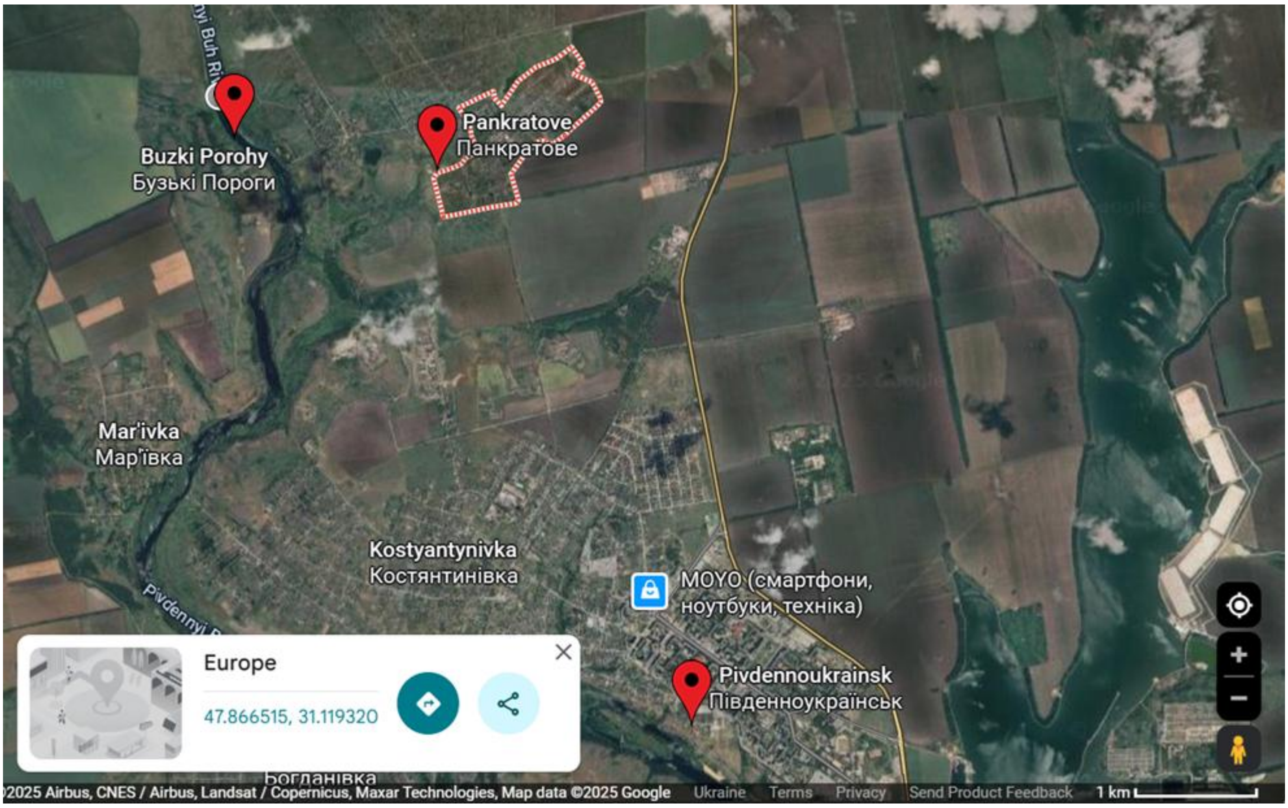


Fig. 1. Drinking water intake site (village of Pankratove) of the city of Yuzhnoukrainsk

the basin is located within the territory of the Ukrainian Crystalline Shield. Only the river's sources lie within the Volhynian-Podolian Plate, while the mouth section belongs to the Black Sea Depression. The upper and middle courses pass through the Volhynian-Podolian and Dnipro Uplands, while the lower part is situated in the Black Sea Lowland.

According to physical-geographical zoning, the basin partially covers the broad-leaved forest zone and fully includes the forest-steppe and steppe zones. Within the administrative division of the territory, the Southern Bug River and its tributaries flow through the Khmelnytskyi, Vinnytsia, Kirovohrad, Mykolaiv, Cherkasy, and partially the Odesa and Kyiv regions.

Along the river's course, three sections are distinguished, which differ significantly from one another: Upper, Middle, and Lower Pobuzhzhia. The studied section of the river belongs to the Middle Pobuzhzhia (from Vinnytsia to the village of Oleksandrivka in the Voznesensk district of the Mykolaiv region). The valley here is wider than in the previous section and ranges from 1 to 2 km. The channel is also different – unlike the previous section with small rapids, here there are many rapids, and the banks are steep, rocky, and elevated in certain segments. The flow velocity in this section is higher than in the previous one and reaches 3–4 m/s.

The basin of the Southern Bug River belongs to one of the key agro-industrial regions of Ukraine, where both agricultural and industrial activities are intensively developed. Among the sectors contributing the largest volumes of discharges into surface waters of the basin, agriculture leads (44.1%), followed by municipal utilities (31.9%) and industry (23.6%).

After treatment at municipal treatment facilities, wastewater is discharged into the Southern Bug or its first- and second-order tributaries. However, most treatment systems are worn out, and the volumes of wastewater often exceed the design capacities, leading to the discharge of insufficiently treated wastewater into water bodies.

The majority of the territory is under significant agricultural influence: agricultural lands occupy about 81% of the total basin area, and in certain sub-catchments this figure ranges from 74% to 90%.

Within the Mykolaiv region, the main sources of pollution are: MKP «Mykolaivvodokanal» (Mykolaiv city), KP «Olshanske» (urban-type settlement of Olshanske), KP «Pervomaisk City Water Utility» (Pervomaisk city), KP «Prybuzke» (Nova Odesa city), «City Water Utility» (Bashtanka city), as well as the South Ukraine Nuclear Power Plant. It is worth noting that MKP «Mykolaivvodokanal» discharges already treated wastewater directly into the Southern Bug Estuary.

Thus, the main types of economic activity that create anthropogenic pressure on the water resources of the Southern Bug River basin include the housing and utilities sector, industrial production, agriculture along with fisheries, hydropower, and flood control measures.

The natural conditions of the Southern Bug River basin, along with the impact of economic activity, form specific features of its hydrochemical regime. The river is characterized by increased water mineralization, which intensifies closer to the mouth – this is explained by the geological characteristics of the territory. At the same time, the waters of the Southern Bug are saturated with dissolved oxygen, which can be attributed to the presence of rapids where active mixing of water masses occurs.

Our general assessment of the pollution level shows that throughout the entire observation period there is high variability in total nitrogen, ammonium ($NH_4^+$), nitrite ($NO_2^-$), and nitrate ($NO_3^-$) ions. The highest concentrations were recorded in 2005–2008, 2013, 2020, and after 2022, which indicates regular inflows of anthropogenic organic matter. Probable sources include sewage discharges, fertilizer leaching from agricultural lands, and accidental pollution.

The content of phosphate ions ($PO_4^{3-}$) remained stable during 2003–2019, but since 2020 a gradual increase has been observed, which may be associated with the use of phosphate-containing detergents or mineral fertilizers.

Chemical oxygen demand (COD) and biochemical oxygen demand over 5 days ($BOD_5$) show similar trends with multiple peaks in 2007, 2010, 2015, and 2023. This indicates regular periods of organic matter inflow into the river. Such peaks coincide with decreases in dissolved oxygen levels, which is a sign of reduced self-purification capacity of the water body.

Permanganate oxidizability, as a general indicator of the presence of organic substances, also shows periodic increases, especially in 2020–2024, indicating a persistent organic load.

Dissolved oxygen is generally maintained at the level of 6–9 $mgO_2/dm^3$, which is acceptable for most aquatic ecosystems. However, in certain periods (2016, 2020, 2023), a decline in concentration is observed, associated with increased organic load or changes in the hydrodynamic regime. Such oxygen deficits pose risks to aquatic fauna and the microbiocenosis.

The content of sulfate ions ($SO_4^{2-}$) depends on seasonality and shows interannual fluctuations with a tendency to increase after 2018. Peaks in 2020 and 2023 are the result of erosion processes, leaching of agricultural lands, or the use of sulfur-containing fertilizers.

The content of chloride ions ($Cl^-$) increases steadily throughout the entire period. A particularly sharp rise is recorded after 2020, indicating reduced water flow, prolonged evaporation, and the impact of sewage discharges.

Synthetic surfactants are generally at low levels; however, since 2022 a gradual increase has been observed. Atrazine and simazine, as herbicides of agricultural origin, are present in the water at a consistently low level. Their presence indicates chronic influence of the agricultural sector on water quality.

Suspended solids show uneven dynamics with periodic increases, particularly in 2013–2015, 2020, and 2024.

Phytoplankton is recorded in moderate concentrations, indicating relative stability of the trophic status of the water body; however, its increase after 2022 signals the development of eutrophication.

The aquatic system of the Southern Bug River in the area of the village of Oleksiivka (village of Pankratove) demonstrates a stable biogenic-organic load, intensified during 2020–2024. The increase in nitrogen, phosphate, surfactants, and herbicides content indicates systematic influence of domestic and agricultural pollution sources. The COD/$BOD_5$ trends, combined with a decline in dissolved oxygen, point to a reduction in aeration potential and a risk of hypoxia.

We will now conduct a more detailed analysis in the context of the following indicators: phosphate ions, ammonium ions, sulfate ions, chloride ions, $BOD_5$, and dissolved oxygen.

Figure 2 shows the results of the analysis of the dynamics of changes in the content of ammonium ($NH_4^+$) and phosphate ($PO_4^{3-}$) ions in the water during the period from 2003 to 2024.

The data indicate significant interannual variability, especially during the period from 2003 to 2012, when frequent peak discharges of both indicators were observed. This is likely related to irregular discharges of untreated or insufficiently treated wastewater, particularly from domestic and agricultural sources. In the period from 2013 to 2019, a certain stabilization of ammonium concentrations is observed; however, periodic spikes indicate recurring episodes of anthropogenic impact. The content of phosphate ions during this period is variable, with some anomalous increases (for example, in 2016 and 2019).

After 2020, a general decrease in the content of phosphates and ammonium in the Southern Bug River is noted, which potentially indicates a reduction in pollution sources or improvements in water treatment systems. At the same time, in 2023–2024, a sharp increase in phosphates and a decrease in ammonium levels are observed.

These trends can be explained as follows. First, there was a significant reduction in the amount of mineral fertilizers applied by agricultural producers in the Mykolaiv region. Thus, while 194 kg of mineral fertilizers (in active substance) per hectare were applied for the 2021 crop, this figure decreased to 138 kg/ha in 2022, and in the following years, 2023–2024, it amounted to 82 kg/ha and 98 kg/ha, respect-

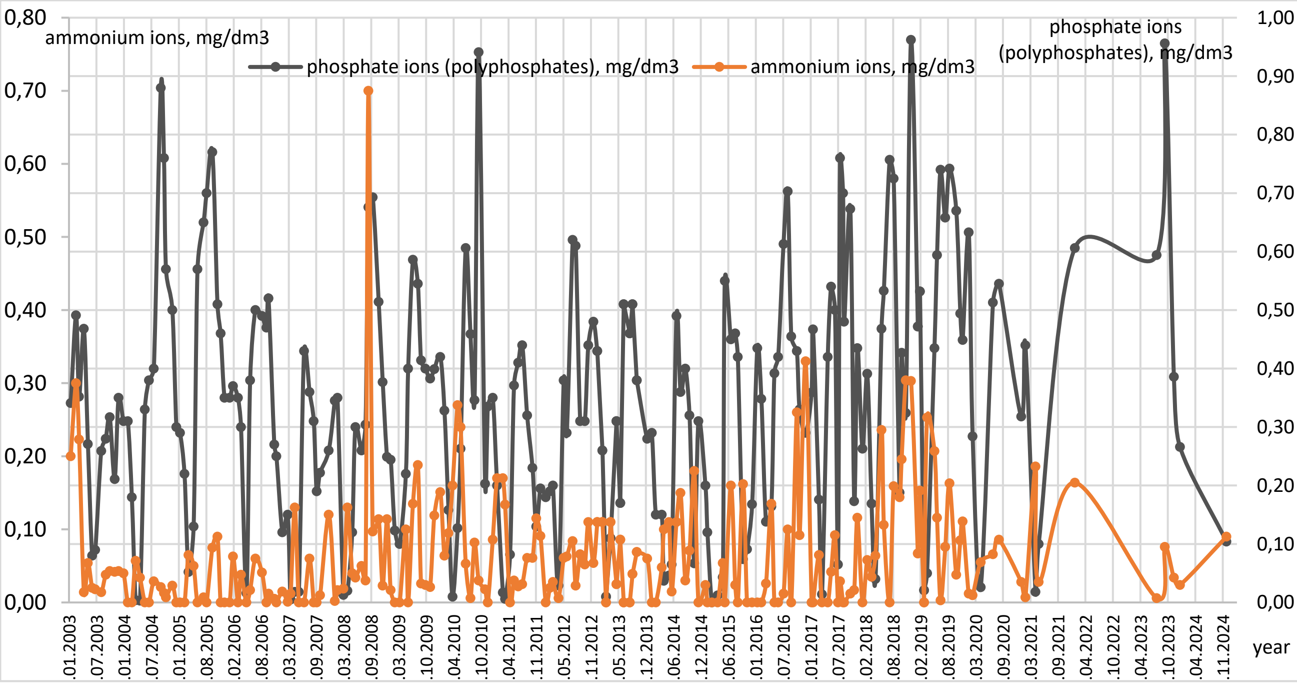


Fig. 2. Dynamics of ammonium and phosphate ion concentrations in the water of the Southern Bug River (village of Oleksiivka, drinking water intake of the city of Yuzhnoukrainsk) in 2003–2024.

ively. This is due to the fact that with the onset of the war, the ability of farmers to use mineral fertilizers changed. Ukraine ceased supplies of fertilizers such as urea, UAN (urea-ammonium nitrate), ammonium sulfate, NPK fertilizers, and potassium chloride from Belarus. As a result of rising European prices for these fertilizers, their import into Ukraine became more difficult for agricultural producers. Due to the shutdown of major nitrogen fertilizer producers in Ukraine since the beginning of the war, prices for them increased, which reduced their use by agricultural producers and, consequently, led to a decrease in the content of ammonium ions in the Southern Bug River. Based on the obtained data, it can be concluded that the underuse of nitrogen fertilizers was compensated by the use of phosphate fertilizers, which led to an increase in the amount of phosphate ions in the water of the Southern Bug.

Secondly, unfortunately, domestic wastewater remains, which contains residues of detergents and, accordingly, pollutes surface waters with phosphates.

The inverse trends between $NH_4^+$ and $PO_4^{3-}$ in certain years indicate competition for biogenic uptake (for example, during algal blooms); oxygen degradation, during which phosphates settle into bottom sediments; or differences in the sources of input (organic wastewater – ammonium, detergents – phosphates).

Figure 3 shows the results of the analysis of the dynamics of sulfate ($SO_4^{2-}$) and chloride ($Cl^-$) ion concentrations, as indicators of mineralization and hydrochemical stability of river waters.

During the period from 2003 to 2020, the concentrations of both ions fluctuated within a wide range (chlorides: 30–70 mg/dm³, sulfates: 80–120 mg/dm³), reflecting both natural seasonal variations and the influence of anthropogenic sources – particularly domestic and industrial wastewater.

After 2020, a clear divergence in the behavior of the indicators is observed: the chloride level stabilizes at a lower level, while the concentration of sulfates rises sharply and remains elevated in 2022–2024. This indicates an increased load from sources related to detergents, agriculture, or the oxidation of sulfur-containing organic residues under conditions of reduced oxygen availability.

The increase in sulfates without a corresponding rise in chlorides indicates the activation of biogeochemical processes in the aquatic environment, particularly sulfate reduction and the influx of technogenic sulfate sources. Such dynamics are a sign of ecological imbalance.

Figure 4 presents the results of the analysis of the relationship between the level of dissolved oxygen (DO) and biochemical oxygen demand over five days ($BOD_5$) during the period from 2003 to 2024, which are key indicators of the degree of organic pollution and the self-purification capacity of the water body.

Throughout the entire observation period, a typical inverse relationship between these two parameters is observed. In years with elevated $BOD_5$ values (for example, 2006, 2009, 2015, 2020–2021), the level of dissolved oxygen decreases. This indicates intensive oxygen consumption by microorganisms decomposing organic pollutants.

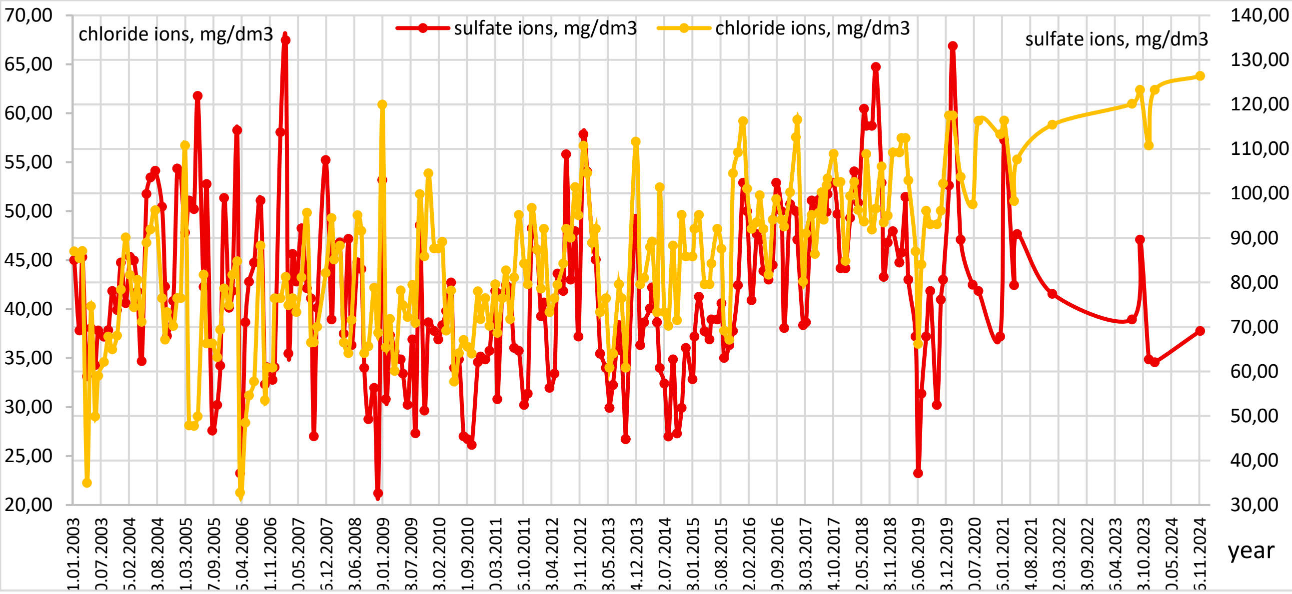


Fig. 3. Dynamics of changes in sulfate and chloride ion concentrations in the water of the Southern Bug River (village of Oleksiivka, drinking water intake of the city of Yuzhnoukrainsk) in 2003–2024

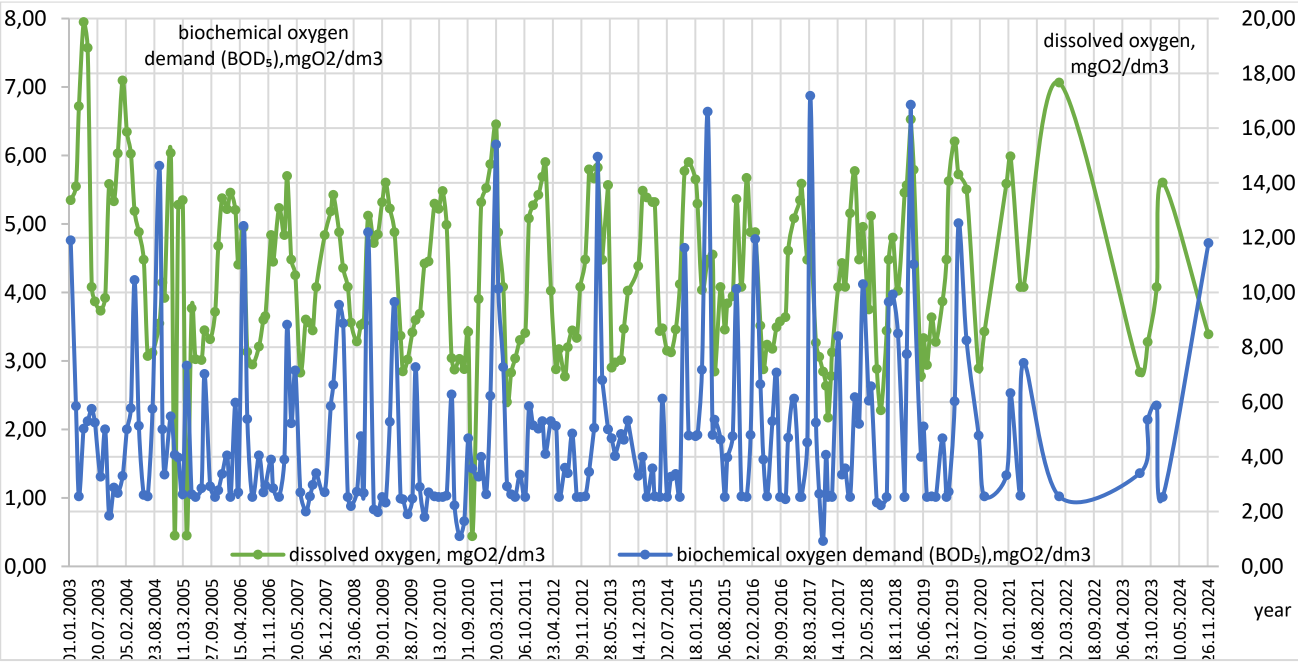


Fig. 4. Dynamics of dissolved oxygen concentration and biochemical oxygen demand ($BOD_5$) in the water of the Southern Bug River (village of Oleksiivka, drinking water intake of the city of Yuzhnoukrainsk) in 2003–2024

At the same time, during periods with relatively low $BOD_5$ levels (2007, 2012, 2018), an increase in DO is observed, which indicates a reduction in organic load and improved aeration conditions.

Starting from 2020, an increase in the amplitude of fluctuations in both indicators is observed, which is associated with the instability of sources of organic pollution or changes in the hydrological regime of the river. Particularly notable is the drop in dissolved oxygen concentration in August 2023, which can be explained by a certain increase in $BOD_5$; thus, oxygen was consumed for the oxidation of organic substances in the water. In addition, the maximum permissible concentration (MPC) for $BOD_5$ was exceeded in December 2024 for the first time since 2020, under conditions of low dissolved oxygen levels. This indicates pollution of surface waters and oxygen consumption for the oxidation of organic contaminants.

Overall, the data confirm the sensitivity of the river ecosystem to organic loading. $BOD_5$ values above 3–4 $mgO_2/dm^3$, in combination with reduced DO, indicate an increased risk of aquatic environment degradation.

Figure 5 presents the results of statistical analysis of the dynamics of changes in the values of the studied indicators during the period from 2003 to 2024.

For visualization, «box-and-whisker» diagrams were used to show the distribution of surface water indicators of the Southern Bug River, including minimum and maximum values, first and third quartiles, as well as the median.

As we can see, the interquartile range, which indicates dispersion, for dissolved oxygen, phosphate, sulfate, and chloride ions demonstrates a moderate level of variation. Exceptions are ammonium ions and $BOD_5$, for which the spread is more significant.

Table 1 presents a comparison of the average values of the studied indicators with their median values.

As observed, the median and arithmetic mean values are practically the same for most indicators, except for ammonium ions and $BOD_5$. This indicates the presence of anomalous values (either low or high) during the period 2004–2024. Other indicators exhibited more stable trends over the years. The median, as is well known, is a more robust measure of central tendency, less sensitive to such outliers, and better reflects the typical value in a dataset. However, in this case, both the arithmetic mean and the median values do not exceed the maximum permissible concentrations (MPC). This gives reason to conclude that, despite the presence of occasional instances of increased surface water pollution in the Southern Bug River, the river demonstrates a capacity for self-purification.

In order to determine the relationship between different pollutants in the surface waters of the Southern Bug River, correlation matrices were constructed for two periods – from 2003 to 2024 and from 2016 to 2024. It was established that for the first period, there is a positive correlation between sulfate and chloride ions (0.48841), and a negative correlation between phosphate ions and $BOD_5$ (–0.33761).

Figure 6 presents the results of the analysis of averaged indicators (arithmetic mean) of changes in the concentrations of ammonium ions ($NH_4^+$, orange line) and phosphate ions ($PO_4^{3-}$, dark gray line) in

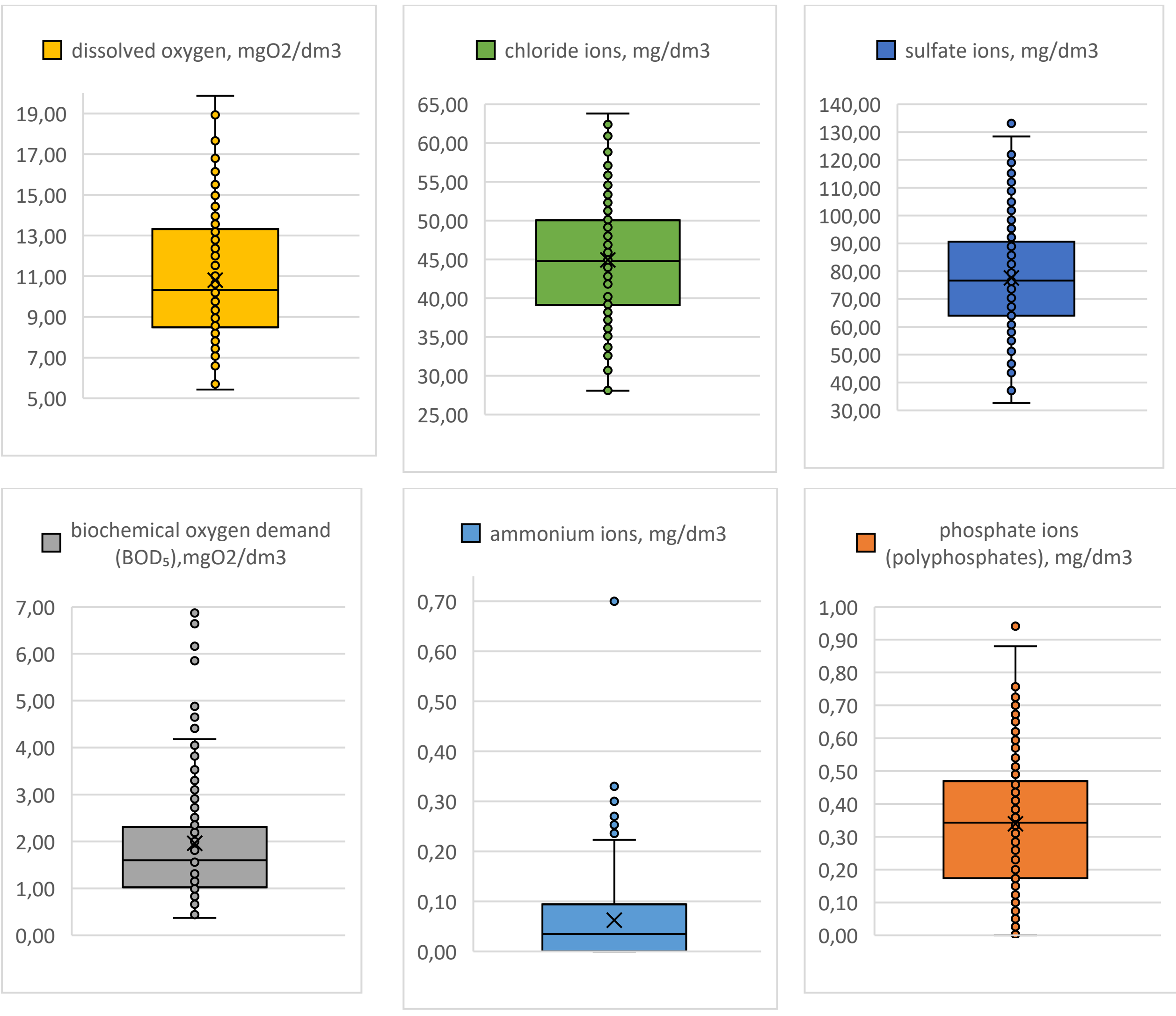


Fig. 5. Statistical analysis of pollution dynamics indicators of the Southern Bug River

*Table 1*

Comparative analysis of arithmetic mean and median values of pollutant concentration indicators

| | ammonium ions, mg/dm³ | phosphate ions, mg/dm³ | biochemical oxygen demand (BOD₅), mgO₂/dm³ | dissolved oxygen, mgO₂/dm³ | sulfate ions, mg/dm³ | chloride ions, mg/dm³ |
|---|---|---|---|---|---|---|
| MPC (Maximum Permissible Concentration) | 0,5 | 3,5 | 3,00 | 4,00 | 100,00 | 350,00 |
| Arithmetic mean value | 0,0625 | 0,3395 | 1,9618 | 10,8035 | 77,5747 | 44,9376 |
| Median value | 0,0350 | 0,3410 | 1,6000 | 10,3600 | 76,8000 | 44,9000 |

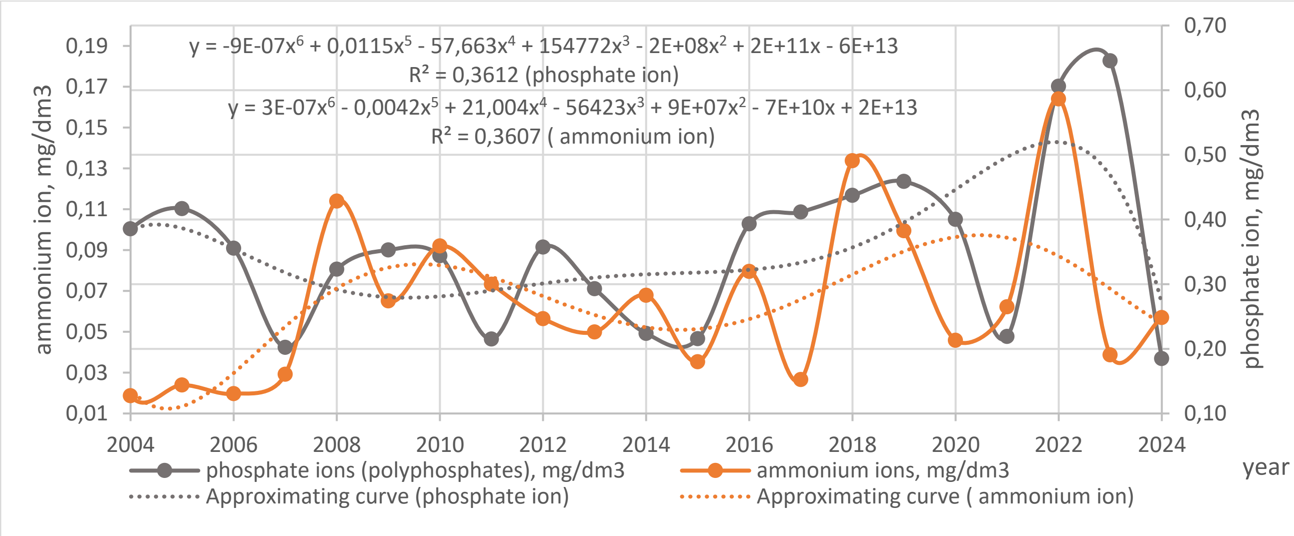


Fig. 6. Dynamics of changes in phosphate and ammonium ion concentrations in the water of the Southern Bug River (village of Oleksiivka, drinking water intake of the city of Yuzhnoukrainsk) in 2004–2024 with approximation curves

the water during 2003–2024.

Approximating curves have been constructed to illustrate the general long-term trends in the concentration changes of two key biogenic components – mineral nitrogen and phosphorus. As previously shown, the arithmetic mean values are sufficiently close to the median values, and therefore the use of arithmetic means is entirely acceptable.

The approximation equation for ammonium ions ($NH_4^+$):

$$y = -3\times10^{-6}x^6 + 0.0255x^5 - 102.76x^4 + 2.0681\times10^5x^3 - 2\times10^8x^2 + 8\times10^{10},$$

with a coefficient of determination $R^2 = 0.3607$.

Maximum concentrations of ammonium were observed in 2008, 2018, and 2022, which is associated with the inflow of domestic wastewater and a decrease in nitrification efficiency due to reduced dissolved oxygen.

The approximation equation for phosphate ions ($PO_4^{3-}$):

$$y = -9\times10^{-7}x^6 + 0.0115x^5 - 57.663x^4 + 1.54772\times10^3x^3 - 2\times10^8x^2 + 2\times10^{11}x - 6\times10^{13},$$

with a coefficient of determination $R^2 = 0.3612$.

Phosphate ions show clear maxima in 2005, 2013, 2019, and 2023, with minima in 2010, 2016, and 2024. This indicates an uneven inflow of phosphorus compounds, originating from detergents or agricultural sources.

The overall dynamics indicate that during the studied period there was a periodic increase in the concentrations of both components, with certain asynchronous fluctuations. This confirms the complexity of the biogeochemical interaction between nitrogen and phosphate compounds in the aquatic environment, driven both by anthropogenic influence and internal transformation processes (biogenic uptake, desorption, anoxic release).

Figure 7 presents the results of the analysis of the averaged concentrations of sulfate ($SO_4^{2-}$) and chloride ions ($Cl^-$) in the surface waters of the Southern Bug River during 2003–2024. These values represent the arithmetic means of the respective ion concentrations. Such averaging levels out seasonal variability but allows for modeling with the construction of polynomial approximation curves, making it possible to identify general trends in mineralization over the period 2004–2024.

Approximation equation for sulfate ions (mg/dm³):

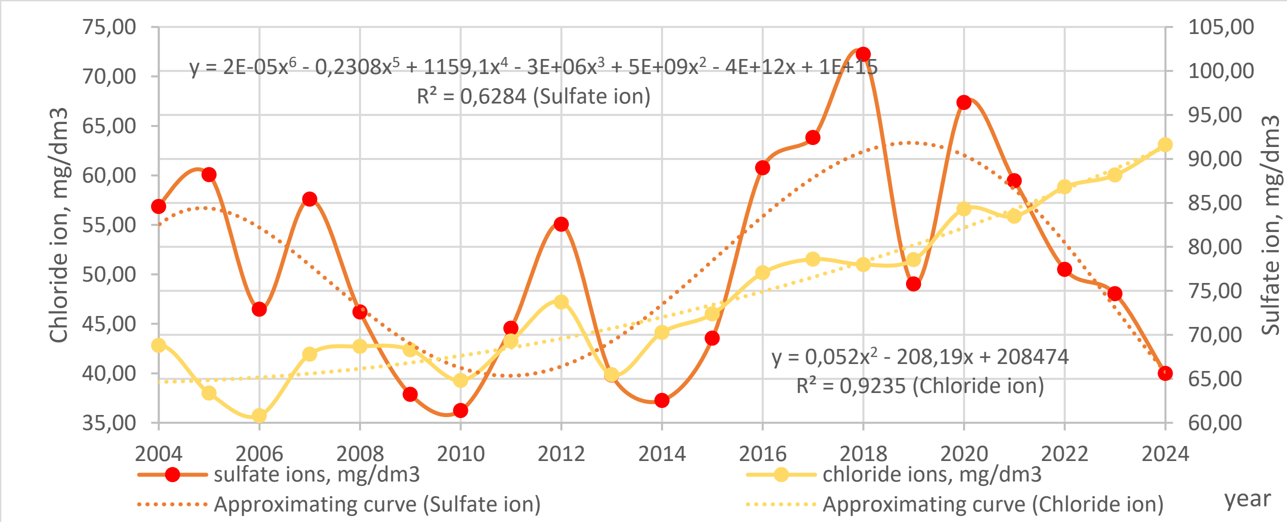


Fig. 7. Dynamics of changes in sulfate and chloride ion concentrations in the water of the Southern Bug River (village of Oleksiivka, drinking water intake of the city of Yuzhnoukrainsk) in 2004–2024 with approximation curves

$y = 2\times10^{-5}x^6 - 0.2308x^5 + 1159.1x^4 - 3\times10^6x^3 + 5\times10^9x^2 - 4\times10^{12}x + 1\times10^{15}$, coefficient of determination $R^2 = 0.6284$**,** which indicates acceptable model reliability.

Approximation equation for chloride ions ($mg/dm^3$):

$y = 0.052x^2 - 208.19x + 208474$, coefficient of determination $R^2 = 0.9235$, which indicates a high degree of model fit to the actual data.

In the early years of the analyzed period (2004–2010), the concentrations of both ions fluctuated with periodic decreases, which is associated with changes in the water balance or limitations in the sources of mineral pollution. Starting from 2012, chloride concentrations show a clear and steady increase, which is related to the influence of agricultural activities or the accumulation of salts in the water body due to reduced flow.

The reasons for such an increase include the presence of domestic wastewater, as a significant amount of insufficiently treated effluents enters the surface waters of the Southern Bug River. In addition, additional anthropogenic pressure may result from fertilizer runoff – specifically potassium chloride – from agricultural lands. Furthermore, a common issue for the Southern Bug, as well as many rivers in southern Ukraine, is the gradual reduction in water flow.

Sulfates, in turn, reached peak values in 2018–2020, after which their levels began to decline. This indicates both changes in pollution sources and chemical reactions in the aquatic environment associated with shifts in pH or the formation of sediment deposits.

The overall trend confirms a tendency toward increasing water mineralization, especially due to the growth in chloride levels, which is an indicator of salt accumulation in the system and potential deterioration of water quality.

Figure 8 presents the results of the analysis of averaged values of biochemical oxygen demand over 5 days ($BOD_5$, blue line) and dissolved oxygen concentration (green line) in the water during the period 2004–2024, along with the corresponding approximation curves that illustrate the general trends in the changes of these indicators.

Approximation equation for $BOD_5$ ($mgO_2/dm^3$):

$$y = 6\times10^{-7}x^6 - 0.0077x^5 + 39.553x^4 - 1.0791\times10^5x^3 + 2\times10^8x^2 - 1\times10^{11}x + 5\times10^{13},$$

coefficient of determination $R^2 = 0.3889$, which indicates low reliability of the model describing the trend of this indicator.

Approximation equation for dissolved oxygen ($mgO_2/dm^3$):

$$y = 5\times10^{-6}x^6 - 0.0568x^5 + 285.69x^4 - 7.66601\times10^3x^3 + 1\times10^9x^2 - 9\times10^{11}x + 3\times10^{14},$$

coefficient of determination $R^2 = 0.4155$, which indicates considerable variability in dissolved oxygen concentrations during the period.

During 2004–2012, $BOD_5$ values remained relatively stable, but starting from 2015 a trend of gradual increase is observed, reaching peak values in 2020–2024. This indicates growing organic load associated with intensified anthropogenic impact.

High concentrations of dissolved oxygen were recorded in 2004, 2010, 2018, and 2022, while significant declines indicating hypoxic conditions were observed in 2006, 2009, 2015, and 2023.

Thus, during the period from 2003 to 2021, there were years when a classical inverse relationship between $BOD_5$ and dissolved oxygen was observed, i.e., increased organic load (higher $BOD_5$)

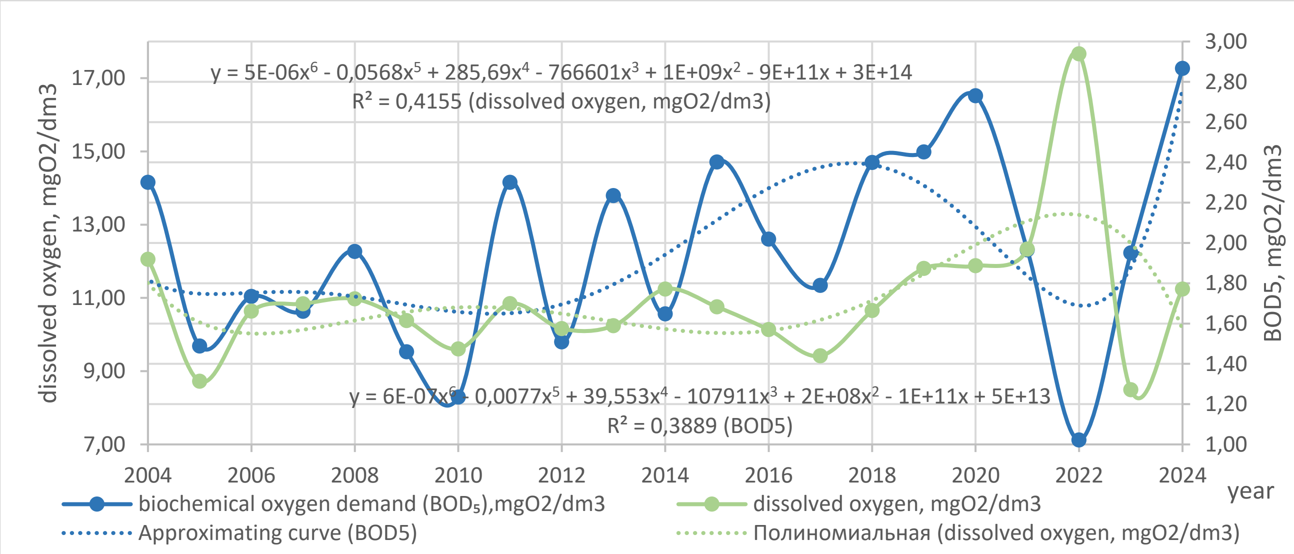


Fig. 8. Dynamics of changes in biochemical oxygen demand ($BOD_5$) and dissolved oxygen concentration in the water of the Southern Bug River (village of Oleksiivka, drinking water intake of the city of Yuzhnoukrainsk) in 2004–2024 with approximation curves

was accompanied by a decrease in oxygen content. However, there were also periods when this relationship was disrupted.

During 2022–2024, a classical pattern re-emerged – an increase in dissolved oxygen was accompanied by a decrease in $BOD_5$. A decrease in $BOD_5$ means there are fewer organic substances in the water that require decomposition, and therefore less oxygen is consumed in the process. Taking into account that in these very years the levels of sulfate and ammonium ions decreased, there is reason to believe that these ions represent the main anthropogenic load on the surface waters of the Southern Bug River.

The gradual increase in chloride content and the periodic (point-source) increases in phosphate ions had a negative impact, but it was not catastrophic in nature.

**Conclusions.** The obtained analysis results allow us to conclude that the aquatic system of the Southern Bug River in the area of the village of Oleksiivka (village of Pankratove) – the drinking water intake for the city of Yuzhnoukrainsk – experiences a stable biogenic-organic load, which intensified in 2020–2024. Increases in nitrogen, phosphates, surfactants, and herbicides indicate systematic influence from domestic and agricultural pollution sources. Trends in COD/$BOD_5$ combined with decreased dissolved oxygen suggest a decline in aeration potential and an increased risk of hypoxia.

It was found that during 2003–2012, irregular discharges of untreated or insufficiently treated wastewater were observed. In 2013–2019, some stabilization in ammonium concentrations was noted, although periodic spikes indicated recurring episodes of anthropogenic impact. During this period, phosphate ion levels fluctuated with individual anomalous increases. After 2020, a general decline in phosphate and ammonium content in the Southern Bug River was recorded, potentially indicating a reduction in pollution sources or improvements in water treatment systems. At the same time, in 2023–2024, a sharp increase in phosphates and a decrease in ammonium levels were observed, associated with a shift in the types of fertilizers used in agriculture – from ammonium-based to phosphate-based.

An analysis of the dynamics of sulfate ($SO_4^{2-}$) and chloride ($Cl^-$) ion concentrations – as indicators of mineralization and hydrochemical stability of river waters – showed that during 2003–2020, the concentrations of both ions varied within a wide range. This was associated both with natural seasonal changes and the influence of anthropogenic sources – in particular, domestic and industrial wastewater. After 2020, the main pollution sources were linked to detergents, agriculture, or the oxidation of sulfur-containing organic residues under low-oxygen conditions.

The results of the analysis of the relationship between dissolved oxygen (DO) levels and biochemical oxygen demand over five days ($BOD_5$) during 2003–2024 showed an inverse interaction between these two parameters. Since 2020, the amplitude of fluctuations in both indicators has increased, which is associated with the instability of organic pollution sources or changes in the river's hydrological regime.

A statistical analysis of the dynamics of changes in the studied indicators during 2003–2024 was conducted and visualized using box-and-whisker plots.

To identify relationships between different pollutants in the surface waters of the Southern Bug River, correlation matrices were built for two periods – 2003 to 2024 and 2016 to 2024. It was found that in the first period there was a positive correlation between sulfate and chloride ions, and a negative one between phosphate ions and $BOD_5$. In the second period, a positive correlation was observed between chloride ions and dissolved oxygen levels, and a negative one between phosphate ions and $BOD_5$.

Forecasting of anthropogenic load levels based on key pollutants was conducted using regression equations, and projected levels of phosphate ions, ammonium ions, sulfate ions, chloride ions, $BOD_5$, and dissolved oxygen in the surface waters of the Southern Bug River were determined.

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# Екологічна оцінка та прогнозування стану поверхневих вод річки Південний Буг на території Миколаївської області

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Питання водозабезпечення та водної безпеки актуалізувались на території України в умовах війни. З урахуванням того, що Україні має розгалужену водну інфраструктуру, яка включає великі багатоцільові водосховища, греблі гідроелектростанцій, охолоджувальні установки для атомних станцій та ін. вплив війни вже сьогодні є екологонебезпечним та катастрофічним. Крім того, в умовах військової агресії поверхневі та підземні води, а також атмосферне повітря зазнають прямого мілітарного впливу. Цей вплив є відчутним як для головних річок, таких як Дніпро, Південний Буг, Інгул, Сіверський Донець, так і для малих річок, а також природних та штучних водойм, прибережних зон Азовського та Чорного морів. Саме тому актуальним є дослідження антропогенного впливу, у т.ч. і під час військових дій, для річки Південний Буг, яка є важливим стратегічним ресурсом для екологічного, соціального та економічного розвитку Миколаївської області України. У роботі представлено результати комплексної екологічної оцінки якості поверхневих вод річки Південний Буг в місті Південноукраїнськ Миколаївської області за період 2003–2024 рр. Досліджено динаміку ключових показників якості води, зокрема вмісту фосфатів-іонів, амонію, сульфатів-іонів, хлорид-іонів, біохімічного споживання кисню ($БСК_5$) та рівня розчиненого кисню. На основі даних Лабораторії моніторингу вод та ґрунтів РОВР у Миколаївській області проведено прогнозування динаміки вмісту забруднюючих речовин за допомогою регресійних моделей та оцінено здатність річки до самоочищення. Отримані результати аналізу дозволяють дійти висновку, що водна система р. Південний Буг у районі с. Олексіївка (с. Панкратове) має стійке біогенно-органічне навантаження, посилене у 2020–2024 рр. Зростання вмісту азоту, фосфатів, ПАР та гербіцидів вказує на систематичний вплив побутових і аграрних джерел забруднення. Тренди ХСК/$БСК_5$ у поєднанні зі зниженням розчиненого кисню свідчать про зниження аераційного потенціалу та ризик гіпоксії. Встановлено, що основне антропогенне навантаження створює промисловість, сільське господарство та комунальні підприємства. Було здійснене прогнозування рівня антропогенного навантаження за основними забруднювачами з використанням регресійних рівнянь та визначені прогнозні рівні фосфат-іонів, амоній-іонів, сульфат-іонів, хлорид-іонів, БСК5 та кисню розчиненого у поверхневих водах р. Південний Буг.

***Ключові слова****: поверхневі води, екологічна оцінка, антропогенне навантаження, забруднення вод, кореляційний аналіз даних, регресійний аналіз, прогнозування.*

**Внесок авторів:** Лідія Горошкова – концептуалізація, ідея, аналіз та інтерпретація даних, написання статті; Олександр Меньшов – ідея, аналіз та інтерпретація даних, моделювання, написання статті; Алла Некос – аналіз та інтерпретація даних, написання статті; Едуард Кочанов – аналіз даних, написання статті; Юлія Корнійчук та Станіслав Горошков – збір вихідних даних, їх систематизація та обробка

**Конфлікт інтересів**: автори повідомляють про відсутність конфлікту інтересів

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