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Study of the influence of war on hydrochemical indicators surface waters of the Dnipro river within the boundaries of the city of Zaporizhzhia and Zaporizhzhia district

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ABSTRACT

Introduction. The Dnipro River is one of the largest river systems in Europe and a key source of surface water in Ukraine, which ensures the functioning of industrial, communal and agricultural water management complexes. Within Zaporizhzhia and Zaporizhzhia District, the river system is subject to the cumulative impact of many years of anthropogenic load caused by the high concentration of the metallurgical, energy, and chemical industries, as well as significant flow regulation due to the functioning of the cascade of Dnipro reservoirs. This forms a complex multicomponent hydrochemical regime with pronounced spatio-temporal heterogeneity of water quality indicators. At the same time, since 2022, the functioning of the Dnipro basin has been affected by an additional extreme factor - military actions, which significantly changed the structure and intensity of anthropogenic impacts on water ecosystems.

The purpose of article. The purpose of this study is a comprehensive assessment of the modern hydrochemical state of the surface waters of the Dnipro River within the city of Zaporizhzhia and the Zaporizhzhia district under conditions of increased anthropogenic and military influence, as well as the identification of the main patterns of spatio-temporal variability of key hydrochemical indicators.

Research methods. Methods of comparison, computer-based statistical data processing using correlation analysis of the results, as well as modeling and forecasting using regression analysis, were applied.

Research results. In order to achieve the stated aim of the study, we selected two monitoring points for the surface waters of the Dnipro River within the city of Zaporizhzhia and Zaporizhzhia District. The analysis was based on data from the Water Monitoring Laboratory of the Basin Water Resources Management of the Azov Rivers and covered the period from 2015 to 2026.

Conclusions. The paper presents the results of a comprehensive environmental assessment of the quality of surface waters of the Dnipro River within the city of Zaporizhzhia and Zaporizhzhia district. The analysis of hydrochemical parameters at the monitoring stations DVS-1 and the village of Bilenke for 2015–2026 indicates a generally relatively stable state of the aquatic environment, with a transition to an unstable regime after 2022 and especially in 2024–2025.

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It is shown that at DVS-1 there is an increase in chemical oxygen demand (COD) without a corresponding rise in biochemical oxygen demand (BOD₅), as well as an increase in suspended solids and mineral components (sulfates and chlorides). This indicates the input of hardly oxidizable and technogenic pollutants as a result of shelling of the city.

In the village of Bilenke, while a stable oxygen regime is maintained, a sharp increase in suspended solids, mainly of mineral origin, is recorded, as well as pulsed changes in biogenic elements due to intense upstream pollution (DVS-1).

The identified features are interpreted as a consequence of wartime impact, manifested through short-term intensive inputs of combustion and destruction products due to increased shelling intensity in Zaporizhzhia in 2025–2026, changes in the hydrological regime, and suppression of natural biogeochemical processes.

Introduction

The Dnipro River is one of the largest river systems in Europe and a key source of surface water in Ukraine, which ensures the functioning of industrial, communal and agricultural water management complexes. Within Zaporizhzhia and Zaporizhzhia District, the river system is subject to the cumulative impact of many years of anthropogenic load caused by the high concentration of the metallurgical, energy, and chemical industries, as well as significant flow regulation due to the functioning of the cascade of Dnipro reservoirs. This forms a complex multicomponent hydrochemical regime with pronounced spatio-temporal heterogeneity of water quality indicators. At the same time, since 2022, the functioning of the Dnipro basin has been affected by an additional extreme factor - military actions, which significantly changed the structure and intensity of anthropogenic impacts on water ecosystems.

Despite a significant number of studies devoted to the assessment of the quality of surface waters of the Dnipro, in modern conditions there is a need to apply complex approaches to the interpretation of changes in hydrochemical indicators, taking into account the simultaneous action of hydrodynamic, industrial and military factors. In this regard, the study of the hydrochemical parameters of the surface waters of the Dnipro River within the boundaries of the city of Zaporizhzhia and the Zaporizhzhia district under the conditions of war is an urgent scientific task aimed at establishing modern laws of the transformation of the water ecosystem, identifying the key factors of water quality changes, and clarifying the mechanisms of the formation of the hydrochemical regime under the conditions of increased anthropogenic pressure in the conditions of war.

The aim of this study. The purpose of this study is a comprehensive assessment of the modern hydrochemical state of the surface waters of the Dnipro River within the city of Zaporizhzhia and the Zaporizhzhia district under conditions of increased anthropogenic and military influence, as well as the identification of the main patterns of spatio-temporal variability of key hydrochemical indicators (in particular, suspended substances, biogenic elements, indicators of organic pollution and oxygen regime).

Within the scope of the goal, identification and quantification of changes in the hydrochemical characteristics of the water environment under the influence of extreme anthropogenic factors of military origin, establishment of their role in the transformation of the self-cleaning processes of the river system and disruption of the natural hydrochemical balance are envisaged.

Research methods. The analysis was based on data from the Water Monitoring Laboratory of the Basin Water Resources Management of the Azov Rivers and covered the period from 2015 to 2026 in the context of the following indicators: phosphate ions, ammonium ions, sulfate ions, chloride ions, nitrates, nitrites, BOD₅, suspended solids and dissolved oxygen.

Methods of comparison, computer-based statistical data processing using correlation analysis of the results, as well as modeling and forecasting using regression analysis, were applied.

Analysis of recent research and publications. The problem of anthropogenic impacts on the state of surface waters is a global one. That is why scientists pay considerable attention in their research both to the analysis of the hydrochemical regime of aquatic systems and to the search for ways to restore and stabilize aquatic ecosystems. The results of recent studies on surface waters in different countries are presented in articles [1–11].

This issue also remains in the focus of attention of researchers studying the condition of the surface waters of the Dnipro River and the sources of anthropogenic impacts that degrade its state [12–22].

The problem of surface water quality of the Dnipro River is one of the key issues in the ecological security system of Ukraine, since this river provides a significant part of the domestic and drinking water supply and functions under conditions of long-term anthropogenic load. The formation of the quality of Dnipro water is determined by a combination of natural-climatic, hydrological, hydrochemical and economic factors, and its assessment requires a comprehensive analysis of biogenic, organic, salt and oxygen indicators. A spatio-temporal approach to water quality assessment makes it possible to identify long-term trends in the deterioration of the state of water ecosystems, associated with the accumulation of

biogenic substances, heavy metals and the weakening of the river's ability to self-clean [12].

A significant contribution to the study of the Dnipro basin was made in the works devoted to the retrospective analysis of hydrochemical indicators and the modeling of the oxygen regime. It is shown that among the most informative indicators of the ecological state of river waters are the ratio between BOD_5 and dissolved oxygen, as well as the content of phosphates and ammonium, which characterize the organic and biogenic load [13-14]. For the Dnipro basin, a trend towards a steady deterioration of the ecological state under the influence of man-made factors has been established, and for forecasting changes in the oxygen regime, it is proposed to use models of the Streeter-Phelps type, which describe the balance between oxygen consumption during the oxidation of organic substances and its supply from the atmosphere. Such approaches create a theoretical basis for the analysis of ecological risks in water bodies, where the state of the oxygen regime directly reflects the level of disruption of self-cleaning processes [15].

A separate area of research is related to the assessment of the salinity of the surface waters of the Dnipro within the city of Zaporizhzhia. For the water intake areas of the city, it is shown that the sum of ions, chlorides and sulfates remain important indicators of anthropogenic transformation of the water environment. Ecological assessment by block of salinity revealed a relatively stable, but not background state of the waters, which is characterized as moderately polluted. This indicates the need to take into account not only biogenic and oxygen indicators, but also mineralization characteristics, since changes in the salt regime determine the ecological stability of the water body and the general hydrochemical stability of the river system in an urbanized environment [16].

With the beginning of a full-scale war, the problem of surface water quality gained new relevance. In modern works, it is emphasized that military operations affect aquatic ecosystems due to the fall into the water of explosion products, fuel and lubricants, fragments of equipment, the destruction of industrial and communal facilities, damage to sewage treatment plants, as well as due to changes in the structure of production and displacement of the population. For the Dnipro River within Zaporizhzhia, according to monitoring data, differences in the behavior of the main indicators of water quality before and after the start of the full-scale war were revealed, in particular for ammonium, BOD_5 , dissolved oxygen, phosphates, sulfates and chlorides. The influence of war does not always manifest itself in the form of linear dependencies, since weather, hydrological,

agrarian and man-made factors are simultaneously imposed on the state of water, but the war itself became a factor that significantly changed the nature of the dynamics of indicators and the structure of connections between them [17].

The further development of this direction is connected with the consideration not only of direct military pollution, but also of the long-term consequences of the destruction of hydrotechnical infrastructure. Research on the suspended sediments of the Dnipro and the Danube shows that the full-scale war caused a transformation of the hydrological and hydrochemical regime of the flow of large rivers, which, in turn, affects sedimentation and lithodynamic processes. The destruction of the Kakhovka Reservoir is considered as one of the largest factors of ecological restructuring of the river system, which changes the transport of suspended matter, the accumulation of pollutants and the conditions of long-term monitoring. In this regard, qualitative and quantitative characteristics of suspended sediments are beginning to be considered as an important addition to traditional hydrochemical indicators, as they reflect the accumulative effect of military and anthropogenic influence [18].

For the immediate Zaporizhzhia section of the Dnipro, modern research has formed a separate body of knowledge about the change in the hydrochemical regime under the influence of the war. In the works that analyzed the state of surface waters in the upper basin of the Dnipro HPP, the main attention was focused on the dynamics of BOD_5 , dissolved oxygen, phosphates and ammonium. It is shown that the oxygen regime is one of the most sensitive indicators of changes in the river ecosystem, and the use of the Streeter-Phelps model makes it possible to estimate the balance between biochemical oxygen consumption and its atmospheric recovery. After the beginning of the war, and especially after the destruction of the Kakhovka HPP, the seasonal rhythms of the behavior of individual indicators changed, and the reduction of phosphate and ammonium concentrations at certain stages contributed to the improvement of self-cleaning conditions. At the same time, such a trend does not mean complete stabilization, since in the event of a return to the pre-war level of pollution, the risks of deterioration of water quality will increase again [6].

This issue is most systematically revealed in works where a comprehensive ecological assessment and forecasting of the state of surface waters of the Dnipro in Zaporizhzhia was carried out for the period 2013-2024. In these studies, it is emphasized that phosphates and ammonium have a pronounced seasonal and anthropogenic nature of fluctuations, sulfates are characterized by high

variability of natural and man-made origin, while chlorides are a more stable indicator of general mineralization. Special attention is paid to the violation of the seasonal dynamics of BOD_5 and dissolved oxygen after 2023, which is associated with the destruction of the Kakhovka dam and the change in the hydrological regime. At the same time, it was concluded that the partial ability of the river to self-recovery is preserved under the conditions of reducing the load of phosphates and ammonium [19].

The use of comparative methodological schemes tested on other river systems of Ukraine is also important for the development of research. In the works devoted to the Southern Bug, a combination of comparative analysis, correlation analysis, and regression forecasting was used to study the dynamics of phosphates, ammonium, sulfates, chlorides, BOD_5 , and dissolved oxygen under wartime conditions. It is emphasized that the combination of these indicators makes it possible to simultaneously assess biogenic load, organic pollution, water mineralization and hypoxia risks. Methodologically, such works are important for the study of the Dnipro within Zaporizhzhia, as they demonstrate the possibility of integrating retrospective monitoring and predictive models into a single scheme for analyzing war-related changes in surface waters [20].

In the broader regional context, the study of bottom sediments and soils of the territories adjacent to the Dnipro, in particular the island of Khortytsia and the drained lakes formed after the destruction of the Kakhovka Reservoir, is also important for the Zaporizhzhia region. Significant excesses in the content of certain heavy metals, high values of magnetic susceptibility and complex relationships between lithogenic and technogenic components were revealed. Although such studies are not directly related to the hydrochemical indicators

of the water column, they significantly expand the understanding of the general geoecological state of the Dnipro coastal-channel system in the Zaporizhzhia region and confirm that the military impact has a multi-component nature and is manifested not only in water, but also in bottom sediments and adjacent landscapes [21–22].

The existing mass of scientific works gives reason to assert that the study of the impact of the war on the hydrochemical indicators of the surface waters of the Dnipro River within the boundaries of the city of Zaporizhzhia and the Zaporizhzhia District is based on several complementary directions: spatio-temporal analysis of the quality of the Dnipro waters, modeling of the oxygen regime, ecological assessment of the salt composition, military-ecological analysis of monitoring series, the study of the consequences of the destruction of the Kakhovka Reservoir and forecasting of changes in aquatic ecosystems in the war and post-war periods

Research results. In order to achieve the stated aim of the study, we selected two monitoring points for the surface waters of the Dnipro River within the city of Zaporizhzhia and Zaporizhzhia District: 1) Dnipro River, 328 km, Zaporizhzhia, municipal drinking water intake (DVS No. 1) (47°81'80" N, 35°10'00" E); 2) Dnipro River, 0 km, drinking water intake of the Bilenke Municipal Enterprise, Bilenkivska Territorial Community, Zaporizhzhia District (47°62'04" N, 35°05'10" E).

The first monitoring point is located in the upper pool of the Dnipro Hydroelectric Power Station (Dnipro Reservoir), while the second is below the Dnipro Hydroelectric Power Station within the Kakhovka Reservoir (the channel of the Old Dnipro).

Fig. 1 shows the results of the analysis of changes in BOD_5 , dissolved oxygen, COD, and suspended solids at monitoring point DVS-1 during 2015–2026.

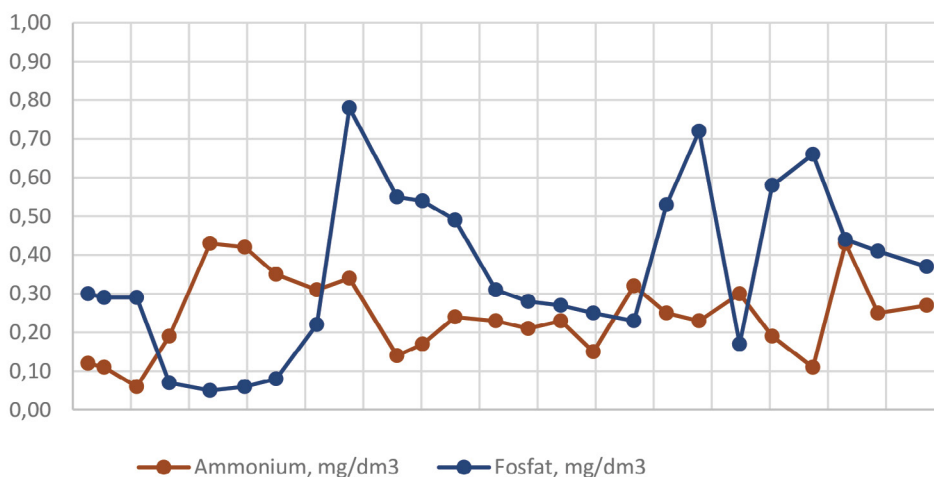


Fig. 1. Dynamics of changes in BOD_5 , dissolved oxygen, COD, and suspended solids at monitoring point DVS-1 during 2015–2026 (January)

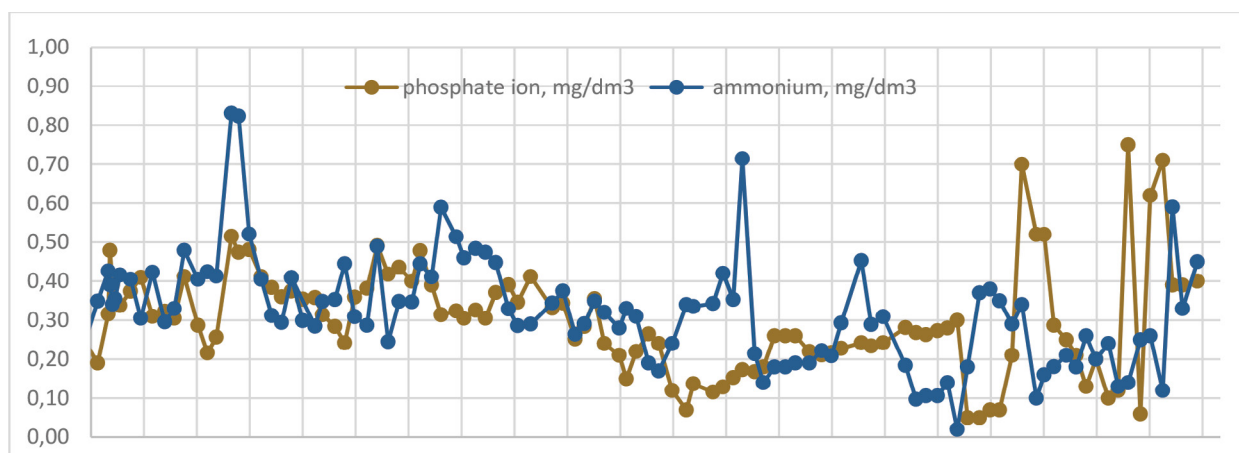


Fig. 2. Dynamics of changes in phosphate and ammonium ion content at monitoring point DVS-1 during 2017-2026 (January)

Analysis of the dynamics of changes in the value of BOD_5 shows that it varies in the range of 2.0-4.0 mgO_2/dm^3 . The COD indicator constantly exceeds BOD_5 and is approximately in the range of 5.5-8.0 mgO_2/dm^3 , which is expected, since it characterizes the total content of both biodegradable and oxidation-resistant organic substances. This may indicate the presence of hard-to-oxidize organic or certain inorganic components in surface waters.

The concentration of dissolved oxygen has a pronounced seasonal character: in the cold period it increases (up to 9-11 mgO_2/dm^3) due to the increased solubility of gases and a decrease in biological activity, while in the warm season it decreases (to 7-8 mgO_2/dm^3) due to the increase in water temperature and the activation of microbiological oxidation of organic matter.

As for COD, a significant increase in this indicator has been noted since July 2025 (with the exception of August and November). At the same time, the situation is atypical, because against the background of the increase in COD, the values of BOD_5 remain almost unchanged, only a slight summer increase is observed, which

does not exceed the levels of previous years. The concentration of dissolved oxygen also maintains the trends characteristic of the previous period.

Another anomaly has been recorded since November 2025 - a sharp increase in the content of suspended solids from the traditional level of about 5 mg/dm^3 to 13 mg/dm^3 , with further increases in the following months. It is worth noting that during the entire period of observation, no such deviations were detected, previously the maximum value was reached only once at the level of 6 mg/dm^3 .

Fig. 2 shows the results of the analysis of changes in phosphate and ammonium ions at monitoring point DVS-1 during 2017-2026 (January).

Concentrations of ammonium NH_4^+ vary in a fairly wide range (0.1-0.8 mg/dm^3). The most noticeable maxima are observed in 2018 (up to ~0.8 mg/dm^3) and in 2022 (about 0.7 mg/dm^3). After 2022, there is a certain decrease with periodic short-term increases. In 2024, minimum values are recorded (in places close to 0.1 mg/dm^3), after which moderate growth is again observed in 2025-2026.

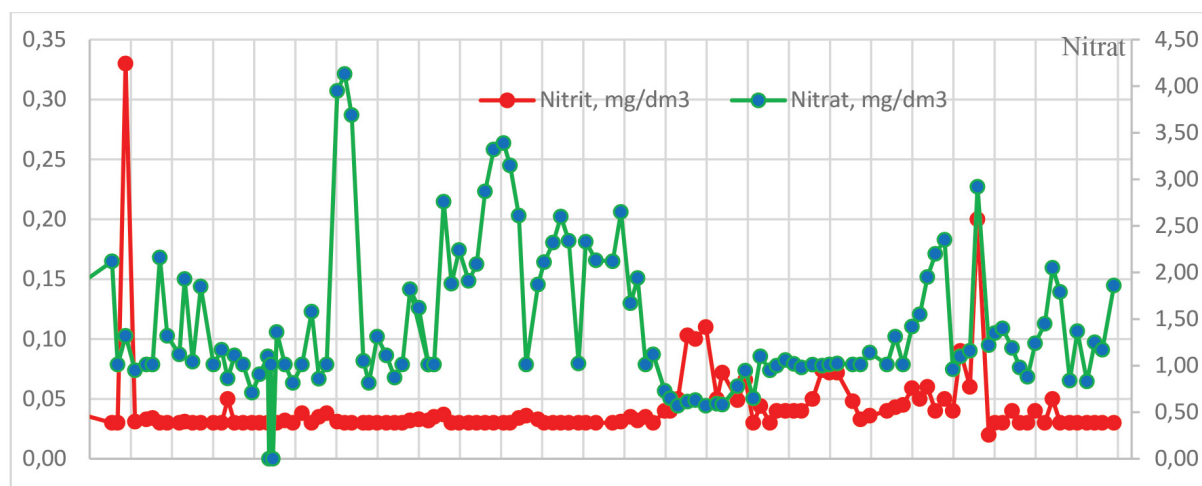


Fig. 3. Dynamics of changes in nitrite (NO_2^-) and nitrate (NO_3^-) concentrations in water for the period 2015-early 2026

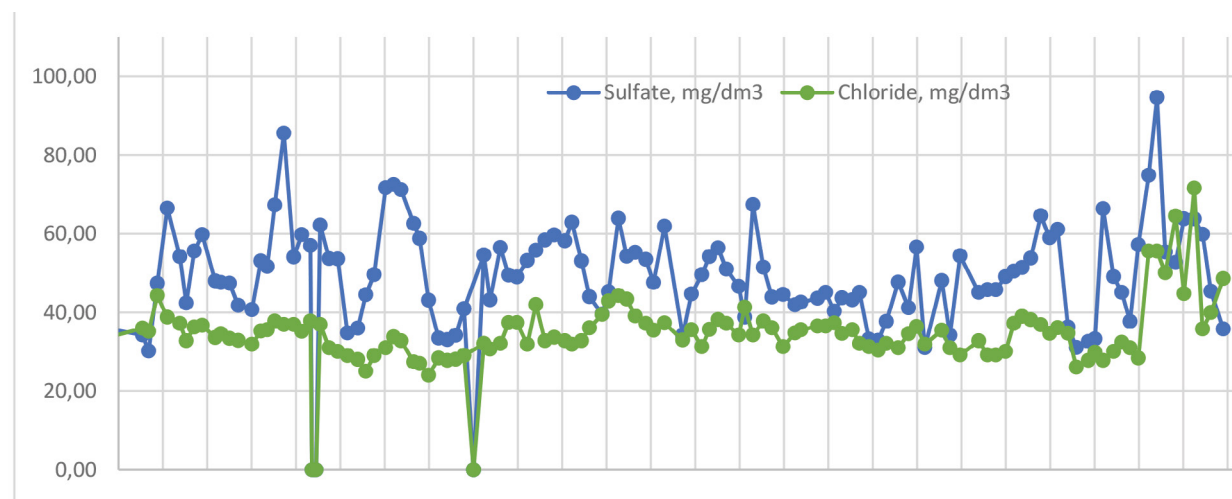


Fig. 4. Dynamics of changes in sulfate ion (SO_4^{2-}) and chloride ion (Cl^-) concentrations in surface waters for the period 2015-early 2026

The content of phosphate ions PO_4^{3-} also varies between 0.2-0.5 mg/dm³ in 2017-2023. Starting from 2024, more pronounced maxima appear - in 2024-2025, concentrations rise to 0.6-0.75 mg/dm³, which are the maximum values for the entire observation period. After the peak values, there are sharp declines, which indicates the instability of phosphate supply.

In 2024-2025, there is a certain asynchrony: phosphate content increases, while ammonium ions often remain at lower levels or fluctuate without sharp maxima at this time. The increase in ammonium may be related to the processes of decomposition of organic matter or additional pollution, while the increase in phosphate, especially in 2024-2025, may indicate an increase in anthropogenic influence.

Fig. 3 presents the temporal dynamics of nitrite (NO_2^-) and nitrate (NO_3^-) concentrations in water for the period 2015-early 2026.

The content of nitrites NO_2^- throughout the period remains mainly low and stable - about 0.02-0.05 mg/dm³. At the same time, sharp peaks that significantly exceed the background values are recorded. The most pronounced surge is observed at the beginning of the period (about 0.33 mg/dm³), as well as separate increases in 2021-2022 (up to ~0.1 mg/dm³) and in 2024 (up to ~0.2 mg/dm³). Such short-term growth may indicate episodic disturbances of nitrification processes or the arrival of fresh organic pollution.

Concentrations of nitrates NO_3^- vary in a much wider range (approximately 0.5-4.0 mg/dm³) and are characterized by more pronounced variability. The highest values were recorded in 2018 (more than 3-4 mg/dm³), as well as in 2019-2020 (about 2-3 mg/dm³). In 2021-2022, there is a decrease to minimum levels (~0.5-1.0 mg/dm³), after which in 2023-2024 there is a gradual increase with individual peaks (up to ~2-3 mg/dm³). In 2025-2026, the values remain moderate, with fluctuations within 1-2 mg/dm³.

Nitrites are an intermediate form in nitrification processes, so their concentrations are usually much lower than nitrates, which is confirmed by the given data.

The maxima of nitrite content, as a rule, do not coincide with the maximum values of nitrates, which indicates the short-term nature of NO_2^- accumulation and its rapid oxidation to NO_3^- .

During periods of increased nitrates (for example, 2018-2020), nitrites remain at a low level, which indicates the effective flow of nitrification processes.

The dynamics of nitrogen forms reflect the variability of biogeochemical processes in the water body. High concentrations of nitrates can be associated with both external input (flushing from the catchment, anthropogenic influence) and active nitrification. Episodic increases in nitrites indicate short-term disturbances in redox conditions or the arrival of fresh pollution. In general, the system is characterized by relative stability, but with periodic anomalies.

Fig. 4 presents the dynamics of sulfate ion (SO_4^{2-}) and chloride ion (Cl^-) concentrations in surface waters for the period 2015-early 2026.

Sulfate concentrations varied between 40-65 mg/dm³, with periodic increases. The most notable maxima are observed in 2017 (up to ~85 mg/dm³) and especially in 2025, where values reach maximum levels for the entire period (~90-95 mg/dm³). In 2018-2022, the dynamics are relatively stable, although fluctuations of average amplitude persist. After 2023, there is an upward trend with sharp short-term spikes.

The chloride content is more stable over a long period of time and is usually in the range of 30-40 mg/dm³. In 2015-2023, minor fluctuations are observed without sharp anomalies. Starting from 2024, a tendency to increase concentrations is noted, and in 2025, sharp peaks (up to ~60-70 mg/dm³) are recorded, which are atypical for the previous period.

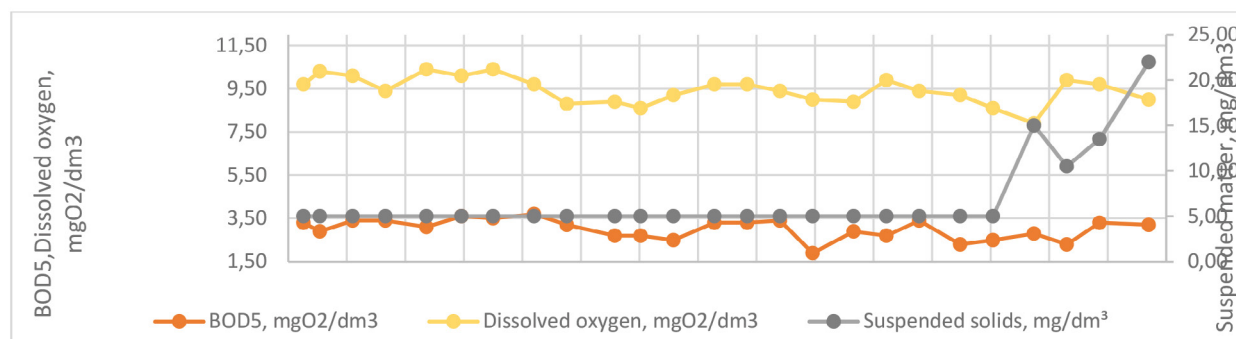


Fig. 5. Dynamics of changes in BOD₅, dissolved oxygen, and suspended solids from January 2024 to January 2026 at the monitoring point - the drinking water intake in the village of Bilenke

During the entire period, the content of sulfates was greater than the content of chlorides. Sulfates had a larger amplitude of oscillations and a more pronounced reaction to changing conditions. In 2025, there is a simultaneous increase in both indicators, which may indicate a common source of income or a change in the hydrochemical regime.

The dynamics of sulfates and chlorides reflects both natural processes (mineralization of water, hydrological conditions) and possible anthropogenic influence. A sharp increase in the content of both ions in 2025, especially after a long period of relative stability, may indicate an increase in man-made load.

Fig. 5 shows the dynamics of changes in BOD₅, dissolved oxygen, and suspended solids from January 2024 to March 2026 at the monitoring point – the drinking water intake in the village of Bilenke.

Throughout the studied period, the BOD₅ concentration fluctuates between 2.0 and 3.5 mg O₂/dm³, which indicates a moderate level of organic pollution. In 2024, this indicator is relatively stable with minor fluctuations, with a short-term decrease in early 2025, followed by a gradual increase in the second half of 2025 to

peak values at the end of the year. The content of dissolved oxygen throughout the period remains quite high and varies between 8.5-10.5 mg O₂/dm³. In 2024, the values are consistently high, in the first half of 2025 there is a slight decrease, and at the end of 2025 - an increase again, which in general indicates favorable conditions of the oxygen regime of the water environment.

The most pronounced changes are characteristic of suspended solids: during 2024 and most of 2025, their concentration remains almost constant at the level of about 4-5 mg/dm³, but from the fall of 2025, there was a sudden increase to maximum values of more than 20 mg/dm³ at the end of the studied period. Such dynamics may indicate the influence of short-term but intense factors, in particular hydrological processes or increased anthropogenic load. In general, there is a stable organic and oxygen water regime against the background of a sharp and abnormal change in the content of suspended matter at the end of the observation period.

Fig. 6 shows the change in ammonium and phosphate ion concentrations in surface waters from January 2024 to January 2026.

The ammonium content fluctuates within the range of approximately 0.05-0.45 mg/dm³

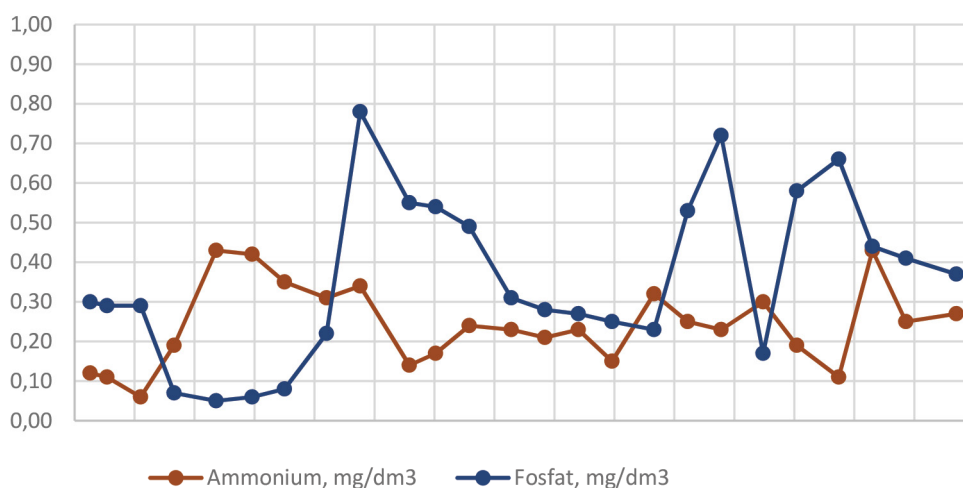


Fig. 6. Dynamics of changes in ammonium and phosphate ion concentrations in surface waters from January 2024 to January 2026

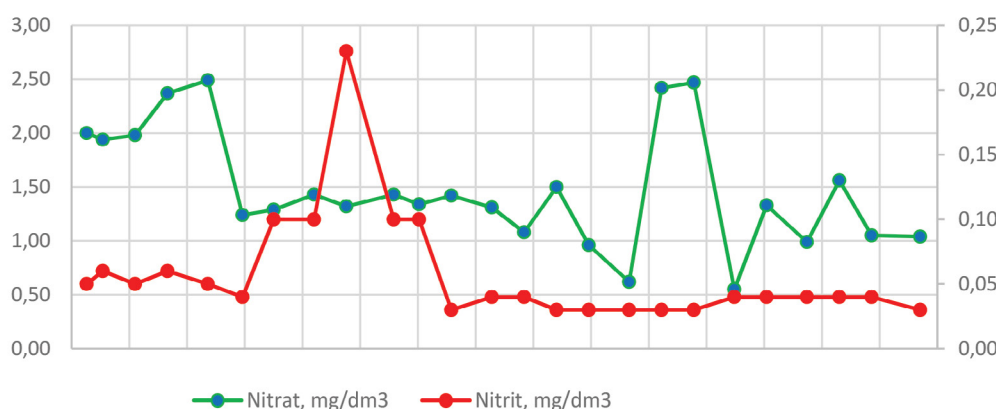


Fig. 7. Dynamics of changes in nitrate and nitrite concentrations in surface waters in the period from January 2024 to January 2026

throughout the entire time. At the beginning of 2024, its values are relatively low, after which there is an increase in the spring and early summer to a maximum of about 0.4-0.43 mg/dm³. In the second half of 2024, the concentration of ammonium decreases and continues to be mainly at a moderate level with minor fluctuations. Throughout 2025, there were ups and downs, with local increases in the middle and end of the year, and at the beginning of 2026, the values stabilize at around 0.25-0.27 mg/dm³.

The concentration of phosphates changes more sharply and in a wider range - from 0.05 to 0.8 mg/dm³. At the beginning of 2024, the content of phosphates was at the level of 0.3 mg/dm³, in the spring there is a decrease to minimum values, after which a sharp peak of almost 0.8 mg/dm³ is recorded in September 2024. In the future, the values gradually decrease at the end of 2024 - the beginning of 2025, but in the summer and autumn of 2025 significant fluctuations are again observed with several pronounced rises above 0.6-0.7 mg/dm³. In general, the graph shows more stable dynamics of ammonium and much more variable dynamics of phosphate content, which may indicate the periodic influence of certain natural or anthropogenic factors on the phosphate regime of water.

Fig. 7 presents the dynamics of nitrate and nitrite concentrations in surface waters in the period from January 2024 to January 2026.

During the entire period, the nitrate content is characterized by moderate variability with fluctuations in the range from 1.0 to 2.5 mg/dm³. In early 2024, nitrate levels are relatively stable and fairly high, increasing to local maxima in the spring, followed by a marked decline in the early summer. In the second half of 2024, the concentration of nitrates fluctuates around the average values. In the spring of 2025, a decrease to the minimum values for the studied period is noted, while in the summer months a sharp increase of nitrates to a level of more than 2.4

mg/dm³ is recorded. In the future, the nitrate content will decrease and at the end of 2025 - at the beginning of 2026 will stabilize at the level of about 1.0-1.1 mg/dm³.

The concentration of nitrites in the water during the entire period is significantly lower, but it is characterized by sharper and more uneven dynamics. In the first half of 2024, nitrite values mostly do not exceed 0.07 mg/dm³, after which there is a pronounced sharp peak in August-September 2024 with an increase to almost 0.25 mg/dm³. After that, the concentration decreases rapidly and during most of 2025 is kept at a relatively low and stable level, around 0.03-0.05 mg/dm³, with minor fluctuations. At the end of 2025, no significant increases in nitrites are observed, and at the beginning of 2026, the values remain low. In general, the obtained data indicate a more stable nitrate water regime and episodic, short-term spikes in nitrite content, which may be associated with temporary disturbances of nitrification processes or external input of nitrogen-containing compounds.

Fig. 8 shows the change in sulfate and chloride concentrations in water for the period from January 2024 to January 2026.

The content of sulfates during the entire period is higher than the concentration of chlorides and is characterized by noticeable variability. At the beginning of 2024, sulfate values are around 55-60 mg/dm³, with a gradual increase to 65-67 mg/dm³ in the spring and early summer, followed by a sharp drop to around 35-40 mg/dm³ in September. At the end of 2024, the concentration of sulfates increases sharply to a local maximum of about 70 mg/dm³, and at the beginning of 2025 it decreases again. In mid-2025, the highest level for the entire monitoring period is recorded — more than 80 mg/dm³, after which the values gradually decrease and approach 40 mg/dm³ by the beginning of 2026. Chloride concentration varies in a narrower range - from 25 to 65 mg/dm³. In 2024, the chloride content was in the range of 30-37 mg/dm³

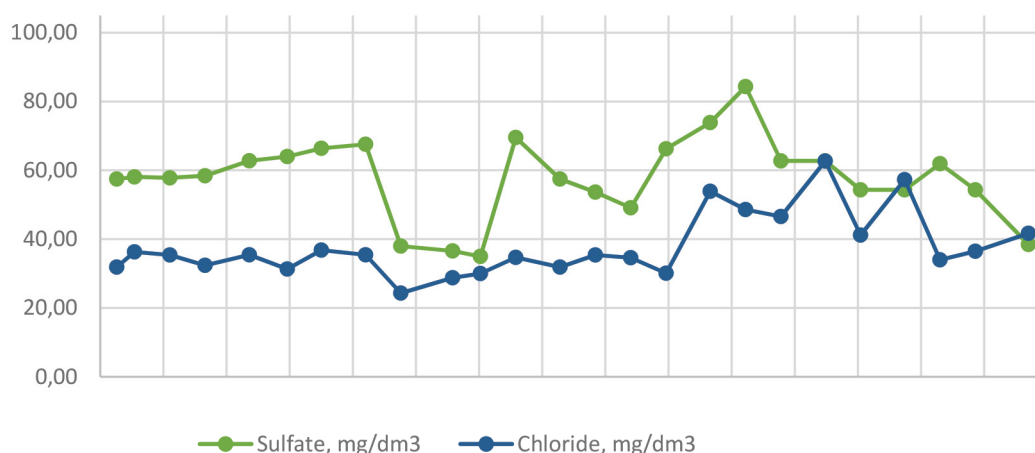


Fig. 8. Dynamics of changes in sulfate and chloride concentrations in water for the period from January 2024 to January 2026

with a short-term decrease to minimum values in autumn. In 2025, an increase is observed in the spring, and a maximum of about 60-65 mg/dm³ was recorded in the summer. At the end of 2025, the concentration of chlorides decreases, and at the beginning of 2026, it stabilizes at the level of about 40 mg/dm³.

A comparative analysis of hydrochemical indicators of surface waters at monitoring points DVS-1 (the upper pool of Dnipro HPP in the city of Zaporizhzhia) and the village of Bilenke, located downstream, indicates the formation of a cascade spatio-temporal response of the water system to anthropogenic and wartime impacts. Given that the city of Zaporizhzhia is subjected to more intense shelling, DVS-1 serves as the zone of primary formation of hydrochemical anomalies, whereas the water intake in the village of Bilenke is the site of their subsequent transformation and accumulation.

In the upper pool, a relatively stable oxygen and organic regime is generally observed: BOD₅ fluctuates within moderate values, and dissolved oxygen remains high. At the same time, COD shows a sharp increase in 2025 without a corresponding rise in BOD₅, which indicates the appearance of organic or technogenic compounds resistant to biochemical oxidation. In Bilenke, these processes manifest themselves differently: COD rises more gradually and persistently, without sharp peaks, which indicates not direct pulse impacts but the accumulation and transformation of pollutants carried by the current.

The most indicative difference is the dynamics of suspended solids. At monitoring point DVS-1, their increase is local and impulsive in nature, associated with direct physical disturbances of the hydrosystem, whereas in Bilenke, in 2025, a sharp and substantial increase in their concentration to more than 20 mg/dm³ was recorded after a long period of stability. This indicates that material mobilized in the upper sections accumulates downstream, and that the additional involvement

of bottom sediments in resuspension processes is also possible. At the same time, the absence of a sharp decrease in dissolved oxygen content in surface waters at both sites indicates the predominantly mineral or weakly biologically active nature of the suspended particles.

Biogenic elements show complex spatial differentiation. In the area of DVS-1, the content of ammonium and phosphate ions is characterized by sharp short-term peaks, which reflects pulsed inflows of pollution and disruption of the stability of biogeochemical processes.

In Bilenke, these same indicators display a smoother but more prolonged dynamics, which points to their gradual transport and secondary redistribution in the aquatic environment.

The nitrate content in both reaches changes relatively consistently; however, in the lower pool these fluctuations are less abrupt, which reflects the equalization of concentrations along the flow. Nitrite content remains low, but episodic peaks, more characteristic of DVS-1, indicate short-term disturbances of nitrification precisely in the zone exposed to more intense impacts.

Mineral components also show clear spatial differentiation. Sharp fluctuations of sulfates and chlorides are observed at DVS-1, especially in 2025, which reflects direct man-made influence and disturbance of the hydrochemical regime.

In Bilenke, these changes appear as a smoother but coordinated increase in both ions, which indicates their transport and accumulation in the lower part of the flow.

Summarizing, it is possible to note a fundamental difference between the two monitoring points (sections of the Dnipro River). At DVS-1, where the impact of military actions is more intense, hydrochemical indicators react quickly, sharply and impulsively, forming local anomalies.

In Bilenke, certain transformations do occur, yet persistent changes are present that reflect the processes of transport, mixing, and accumulation. Thus, the river system performs the function of

a natural integrator of impacts, where the upper pool is the zone of generation of hydrochemical disturbances and the lower pool is the zone of their accumulation and partial transformation. In the context of intensified shelling of Zaporizhzhia, this means that the upper section forms the primary ecological risks, while in the lower section they spread spatially and become fixed in the form of an altered hydrochemical background.

Conclusions. The analysis of hydrochemical indicators at the DVS-1 monitoring point for the period 2015-2026 indicates a generally relatively stable state of the water environment with periodic phases of destabilization, which are especially clearly manifested after 2024.

The organic load, reflected by BOD_5 and COD, has a moderate level in most of the period. At the same time, an atypical situation is recorded in 2025: the level of COD increases significantly (since July), while BOD_5 remains relatively stable. This is an anomaly that indicates an increase in the proportion of hard-to-oxidize organic or even inorganic reducing agents (for example, humic substances, man-made products), without a corresponding increase in biologically available organic substances.

The level of dissolved oxygen has seasonal dynamics: high values in the cold period and a decrease in the warm period. Its inverse relationship with BOD_5 and COD confirms the active use of oxygen in the processes of oxidation of organic matter. At the same time, the absence of a sharp drop in oxygen content even during periods of increased COD (especially in 2025) indicates sufficient aeration of water or the fact that a significant part of the substances that form COD is not involved in intensive biochemical oxidation.

The content of suspended solids remains stable for a long time (~ 5 mg/dm³), which is typical for conditions of a relatively stable hydrological regime. However, a sharp increase at the end of 2025 (up to 13 mg/dm³ and above) is an anomaly. Unlike previous years, when similar values did not exceed 6 mg/dm³ and increases were episodic in nature, this increase is long-lasting. It is probably related to local anthropogenic influence. It is important that this increase is accompanied by an increase in COD, which is consistent with the adsorption of organic substances on suspended particles. Therefore, suspended substances act as a carrier of organic load and additionally affect the oxygen regime, worsening the aeration conditions.

The dynamics of biogenic elements (ammonium and phosphate ions) reflects the variability of both internal processes and external inputs. Ammonium content is characterized by sharp but short-term peaks, which are a typical sign of the influx of fresh organic pollution or the activation of mineralization processes. The decline in

ammonium after the peaks is usually associated with its oxidation to nitrites and nitrates. This is confirmed by the behavior of nitrates, which show a smoother but much broader amplitude of changes (up to 3-4 mg/dm³), with maxima in 2018-2020 and renewed growth in 2023-2024.

Nitrites, as an intermediate form, remain at a low level, but with episodic sharp spikes (especially at the beginning of the period, in 2021-2022 and 2024). Such peaks are an indicator of short-term nitrification disturbances or local oxygen deficiency in microzones. It is important that these spikes do not coincide with nitrate maxima, which indicates the rapid conversion of NO_2^- to NO_3^- and, in general, the effective flow of nitrification processes in the system.

The content of phosphate ions is unstable, especially after 2024, when their concentrations reach maximum values (0.6-0.75 mg/dm³). Unlike ammonium, their increases are of a longer duration and are often not synchronized with nitrogen forms. This indicates a different origin.

The mineral composition (sulfates and chlorides) generally reflects the background hydrogeochemical conditions, but also reacts to external influences. The content of sulfates has a larger amplitude of fluctuations and shows sharp peaks (2017 and especially 2025 — up to 90-95 mg/dm³), which can be associated with both natural processes (oxidation of sulfur-containing compounds) and technogenic influence. The content of chlorides remains stable for a long time, but from 2024 their concentration increases, and in 2025 sharp peaks are recorded (up to 60-70 mg/dm³). Synchronous growth of sulfates and chlorides in 2025 indicates a common source of income.

The impact of the war on the recorded dynamics of hydrochemical indicators at DVS-1 is indirect, but can be clearly traced through a set of anomalies that intensify after 2022 and especially in 2024-2025. It is important to understand that the war does not create «new» processes in the water environment, but sharply changes the intensity and balance of already existing ones - hydrological, biogeochemical, and anthropogenic.

Under conditions involving the use of Shahed-type strike drones and missiles, various substances may enter water bodies, simultaneously causing an increase in suspended solids and a rise in chemical oxygen demand (COD). The sources of such pollution include both explosion products and the components of the technical devices themselves, as well as materials from destroyed infrastructure.

First of all, a significant contribution is made by products of detonation of explosive substances containing organic compounds. During the explosion, partially oxidized organic

residues, nitro compounds and finely dispersed solid particles, in particular soot, are formed. These components increase COD as chemically oxidizable substances and at the same time form the fraction of suspended substances in water.

An important source is also fuel and lubricants - liquid hydrocarbon fuels, lubricating oils and hydraulic fluids, which can enter the water due to equipment damage. They are characterized by a high content of organic carbon, which leads to the growth of COD, and are also able to form emulsions or adsorb on solid particles, indirectly increasing the concentration of suspended substances.

A separate role is played by the debris of the hulls and structures of drones and missiles. Particles of metals, polymers, composites, rubber and insulating materials enter the water. In a finely dispersed state, they directly increase the content of suspended substances, and organic components of polymers with partial degradation can additionally affect the growth of COD.

Combustion products accompanying explosions and fires also have a significant impact. These include soot, polycyclic aromatic hydrocarbons and other partially oxidized organic compounds. They are simultaneously components of suspended substances and a source of increased COD.

In addition, construction materials that enter the water due to the destruction of structures make a significant contribution to pollution. These are cement dust, particles of concrete, bricks, silicates, as well as paints and coatings. Mineral components increase the content of suspended solids, while organic additives and coatings can increase COD.

In addition, heavy metals, electronic components, and electrolytes may appear in the water, which, although they do not always have a direct effect on COD, are capable of suppressing microbiological processes, changing the general nature of the transformation of pollutants.

The increase in ammonium-ion content in surface waters under wartime conditions may be associated with the thermal destruction of nitrogen-containing materials during explosions and fires, as well as with the decomposition of organic and technical substances containing nitrogen. Under normal conditions, ammonium in water undergoes nitrification with the formation of nitrites and nitrates, which is accompanied by oxygen consumption; however, under wartime conditions this process is often suppressed because of the toxic effect of impurities, high water turbidity, and disruption of the functioning of microbiocenoses. As a consequence, ammonium can accumulate in the aquatic environment without a significant effect on BOD_5 and without a noticeable decrease in dissolved oxygen.

Phosphate ions enter the water mainly as a result of the destruction of building materials, washing of dust from man-made surfaces, damage to infrastructure, as well as the release of compounds from soils and man-made deposits. The simultaneous increase of ammonium and phosphate ions at a stable level of dissolved oxygen and the absence of BOD_5 growth indicates the dominance of pulsed man-made input of substances and suppression of natural processes of nitrogen and phosphorus cycles. Under such conditions, the water system accumulates mineral forms of nitrogen and phosphorus without effective biological transformation, while changes in COD and suspended matter reflect the parallel arrival of organic and mechanical degradation products.

The increase in the content of sulfates can be associated with the oxidation of sulfur-containing compounds that are formed during fuel combustion and explosive processes. In particular, sulfur dioxide entering the atmosphere during combustion is oxidized to sulfuric acid in an aqueous environment and further transforms into the form of sulfate ions. An additional source is the destruction of building materials, in particular gypsum and cement components, which contain sulfate compounds. Industrial objects and dust aerosols of mineral origin can also contribute.

Chlorides can enter the water as a result of the burning of polymeric materials, especially those containing chlorine, such as polyvinyl chloride. During the thermal destruction of such materials, hydrogen chloride is formed, which transforms into chloride ions in an aqueous medium. In addition, the source of chlorides can be technical fluids, electrolytes, cooling mixtures and products of the destruction of engineering infrastructure. Chlorides are conservative ions, they do not decompose and are practically not removed from water by natural processes, therefore they tend to accumulate.

The overall dynamics of changes in hydrochemical indicators in the water of the Dnipro River (the village of Bilenke) in 2024-early 2026 indicate a relatively stable state of the oxygen and organic regimes against the background of more dynamic and, in places, anomalous changes in biogenic and mineral components.

Indicators of BOD_5 and dissolved oxygen show an inverse relationship typical for relatively clean or moderately polluted waters. During most of the period, BOD_5 is maintained at the level of 2.0-3.5 mg O_2/dm^3 , while the concentration of dissolved oxygen remains high (8.5-10.5 mg O_2/dm^3). This indicates the balance of biochemical oxidation processes and sufficient water aeration. A slight decrease in oxygen in the first half of 2025 is accompanied by

a relative stabilization or even a decrease in BOD_5 , which is atypical and may indicate not so much an increase in organic load, but the influence of the temperature factor (decrease in oxygen solubility in the warm period) or hydrobiological processes (increased respiration of hydrobionts). Further growth of BOD_5 in the second half of 2025 is logically consistent with an increase in the supply of organic matter (for example, during the summer-autumn development of phytoplankton or the washing of organic matter from the catchment).

At the same time, a sharp increase in the concentration of suspended solids in the fall of 2025 (over 20 mg/dm^3) against the background of their long-term stability ($4\text{--}5 \text{ mg/dm}^3$) is abnormal. This phenomenon is probably of anthropogenic origin. It is important that this growth is not accompanied by a sharp increase in BOD_5 or a decrease in oxygen, which indicates the predominantly mineral nature of the suspended particles. At the same time, the increase in suspended solids could contribute to the adsorption of phosphates and temporary changes in their concentrations.

The content of ammonium ions increases in the spring (2024), which may be associated with flushing from the catchment and mineralization of organic matter, while the subsequent decrease is due to active nitrification. This is confirmed by the behavior of nitrates: their increase in spring and summer reflects intensive oxidation of ammonium. At the same time, the sharp increase in nitrates in the summer of 2025 after the spring minimum is an indicator of either increased inflow from the basin (agricultural runoff) or activation of nitrification processes under favorable temperature conditions.

Nitrites, as an unstable intermediate form, show episodic peaks, the most pronounced of which was recorded in August–September 2024. Such a surge is a classic sign of an imbalance between nitrification stages (oxidation of $\text{NH}_4^+ \rightarrow \text{NO}_2^- \rightarrow \text{NO}_3^-$) or local oxygen deficiency in microzones, even if the total content of dissolved oxygen remains high. This may be due to the arrival of fresh organic matter or local pollution.

Phosphate-ion content is the most variable indicator. Maxima, especially in September 2024 and in the summer-autumn period of 2025, indicate short-term inputs, most likely from wastewater and agricultural runoff. Importantly, these peaks are not always accompanied by a proportional increase in BOD_5 , which may indicate rapid phosphate uptake by phytoplankton or their binding to suspended particles. The relationship between maxima of phosphate content and suspended solids at the end of 2025 may indicate intense resuspension processes in bottom sediments, where phosphorus accumulates in a bound form.

Mineral components (sulfates and chlorides) reflect both natural and anthropogenic factors. The sulfate content has peaks (up to more than 80 mg/dm^3 in 2025), which may be related to industrial discharges or oxidation of sulfur-containing compounds. The content of chlorides does not have sharp maxima, but its increase in 2025 (up to $60\text{--}65 \text{ mg/dm}^3$) indicates an increase in anthropogenic influence (domestic sewage, man-made load). Concordant chloride and nitrate maxima in 2025 may indicate a common source.

For the water intake in the village of Bilenke, the influence of wartime factors likewise manifests itself not as a simultaneous deterioration of all indicators, but as a disruption of the stability of the hydrochemical regime, the appearance of sharp impulse changes, and atypical combinations of indicators, especially in 2024–2025.

First of all, this is visible against the background of a generally stable oxygen and organic regime. BOD_5 throughout the period remains within moderate values, and dissolved oxygen is high. This means that there was no mass influx of easily oxidizable organic matter (for example, large volumes of domestic sewage). At the same time, such «normality» is somewhat misleading, since other indicators show significant disturbances. That is, the war is manifested here not because of classic organic pollution, but because of another type of influence - hydrological and man-made.

The most telling is the sharp increase in suspended solids in the fall of 2025 (more than 20 mg/dm^3 after a long-term level of $4\text{--}5 \text{ mg/dm}^3$). Such a change has the characteristics of a military or related influence. It is important that this increase is not accompanied by a proportional increase in BOD_5 and a drop in oxygen, that is, suspended substances are mainly of mineral or weakly bioavailable origin. This is a typical indicator of mechanical (rather than organic) disruption of the system, which corresponds well with the consequences of military actions.

Thus, in the area of the drinking water intake in the village of Bilenke, the influence of the war manifests itself as a sharp increase in suspended solids without deterioration of the oxygen regime; pulse-like inputs of pollutants, including peaks in phosphate and nitrite content; changes in water mineralization, including the synchronous increase in sulfate and chloride content; and so forth.

Importantly, unlike DVS-1, where the technogenic component is more clearly manifested through COD, in Bilenke the hydrological-geochemical effect predominates - that is, the impact exerted through changes in the physical state of the system (channel, bottom sediments, runoff), and not solely through direct chemical pollution.

Thus, comparing the hydrochemical data with periods of intensified shelling of the city of

Zaporizhzhia makes it possible to interpret the recorded changes as a consequence of short-term but intense inputs of destruction and combustion products into the river system. This is manifested in the form of increasing COD and suspended solids under a relatively stable oxygen regime, which is characteristic of an impact type of pollution rather than of a prolonged organic load. In addition, in our opinion, one may also speak of a cumulative effect of previous impacts which, under conditions

of intensified shelling of the city, manifested themselves in the form of the anomalies under study.

In sum, it is more appropriate to speak not of a catastrophic deterioration in water quality, but of the system's transition to an unstable state, in which, even under normal average values, the frequency and amplitude of anomalies increase sharply, which is a characteristic sign of the influence of wartime factors on aquatic ecosystems.

Конфлікт інтересів: автори повідомляють про відсутність конфлікту інтересів

Внесок авторів: Лідія Горошкова – концептуалізація, розробка ідей, аналіз та інтерпретація даних, написання статті; Олександр Меньшов – розробка ідей, аналіз та інтерпретація даних, моделювання, написання статті; Денис Маслов – аналіз та інтерпретація даних, написання статті; Юлія Корнійчук та Станіслав Горошков – збір первинних даних, їх систематизація та обробка

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Дослідження впливу війни на гідрохімічні показники поверхневих вод річки Дніпро в межах міста Запоріжжя і Запорізького району

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АНОТАЦІЯ

Річка Дніпро є однією з найбільших річкових систем Європи та ключовим джерелом поверхневих вод України, що забезпечує функціонування промислових, комунальних і аграрних водогосподарських комплексів. У межах Запоріжжя та Запорізького району річкова система зазнає кумулятивного впливу багаторічного антропогенного навантаження, зумовленого високою концентрацією металургійної, енергетичної та хімічної промисловості, а також значною зарегульованістю стоку внаслідок функціонування каскаду дніпровських водосховищ. Це формує складний багатокомпонентний гідрохімічний режим із вираженою просторово-часовою неоднорідністю показників якості води. Водночас із 2022 року функціонування басейну Дніпра зазнало впливу додаткового екстремального чинника - воєнних дій, які істотно змінили структуру та інтенсивність антропогенних впливів на водні екосистеми. У роботі представлено результати комплексної екологічної оцінки якості поверхневих вод річки Дніпро в межах м.Запоріжжя та Запорізького району (с. Біленьке). Аналіз гідрохімічних показників у пунктах моніторингу ДВС-1 і с. Біленьке за 2015–2026 рр. свідчить про загалом відносно стабільний стан водного середовища з переходом до нестійкого режиму після 2022 року та особливо у 2024–2025 рр. Показано, що для ДВС-1 характерне підвищення ХСК без відповідного зростання БСК₅, збільшення вмісту завислих речовин і мінеральних компонентів (сульфатів і хлоридів), що вказує на надходження важкоокиснюваних і техногенних домішок внаслідок обстрілів міста. У с. Біленьке за збереження стабільного кисневого режиму фіксується різке зростання завислих речовин переважно мінерального походження, а також імпульсні зміни біогенних елементів внаслідок інтенсивного забруднення поверхневих вод вище за течією (ДВС-1). Виявлені особливості інтерпретуються як наслідок воєнного впливу, який проявляється через короткоточасні інтенсивні надходження продуктів руйнування і горіння внаслідок підвищення інтенсивності обстрілів м. Запоріжжя у 2025 – 2026 рр., зміну гідрологічного режиму та пригнічення природних біогеохімічних процесів.

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поверхневі води, екологічна оцінка, антропогенне навантаження, забруднення вод, вплив війни, гідрохімічні показники, антропогенний вплив, військовий вплив, річка Дніпро, якість поверхневих вод.