

EUTROPHICATION OF THE ODESA COASTAL WATERS BEFORE AND AFTER THE ONSET OF THE FULL-SCALE WAR: ASSESSMENT USING INDIVIDUAL AND COMPLEX INDICATORS FOR 2019–2025

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Eutrophication of coastal marine waters remains one of the key environmental problems of the north-western part of the Black Sea, determining the ecological status of coastal ecosystems and limiting the recreational use of marine areas. In recent years, traditional eutrophication drivers have been supplemented by new forms of anthropogenic impact associated with military activities, disruption of the hydrological regime, and degradation of wastewater infrastructure. The coastal waters of the city of Odesa are particularly vulnerable to these changes, as they are continuously influenced by riverine, estuarine, and urban runoff.

This study presents the results of a comprehensive assessment of eutrophication in the coastal waters of the city of Odesa over a seven-year period (2019–2025), with a focus on the pre-war (2019–2021) and wartime (2022–2025) stages. The analysis is based on data from regular hydrochemical and hydrobiological monitoring conducted by the Ukrainian Scientific Center of Ecology of the Sea, using complex indicators of trophic status and water quality, namely TRIX and EQR (BEAST).

It was established that during the pre-war period the coastal waters of Odesa were characterized by relative stability of indicators and a gradual decrease in the level of eutrophication, corresponding to a moderate trophic status. After the onset of the full-scale war, a disruption of pre-war trends was recorded, along with increased variability of hydrochemical parameters and deterioration of water quality caused by enhanced inputs of nutrients, primarily organic forms of nitrogen. The assessment results based on the complex indicators TRIX and EQR (BEAST) are consistent with each other and confirm a transition of the coastal marine waters of Odesa in 2024–2025 to a high trophic status, which does not correspond to a good ecological status.

The study results indicate a significant impact of wartime factors – particularly the destruction of hydraulic structures, reduced efficiency of wastewater treatment systems, and increased organic loading from estuarine and riverine waters – on eutrophication processes in the coastal waters of Odesa. The obtained assessments may be used to improve environmental monitoring systems and the management of coastal marine waters in the post-war period. *Key words:* eutrophication, coastal marine waters, the Black Sea, Odesa, nutrients, TRIX, EQR (BEAST), wartime impact.

Евтрофікація прибережних вод м. Одеса до та після початку повномасштабної війни: оцінка за індивідуальними та комплексними показниками у 2019–2025 роках. Тітяпкин А.

Евтрофікація прибережних морських вод залишається однією з ключових екологічних проблем північно-західної частини Чорного моря, що визначає екологічний стан прибережних екосистем та обмежує рекреаційне використання акваторій. В останні роки традиційні чинники евтрофікації доповнилися новими формами антропогенного впливу, пов'язаними з воєнними діями, порушенням гідрологічного режиму та деградацією інфраструктури водовідведення. Особливо вразливими до таких змін є прибережні води м. Одеса, які перебувають під постійним впливом річкового, лиманного та міського стоку.

В роботі наведено результати комплексної оцінки евтрофікації прибережних вод м. Одеса за семирічний період 2019–2025 рр. з акцентом на довоєнний (2019–2021) та воєнний (2022–2025) етапи. Аналіз виконано на основі даних регулярного гідрохімічного та гідробіологічного моніторингу, який проводиться Українським науковим центром екології моря, із застосуванням інтегральних показників трофності та якості вод TRIX і EQR (BEAST).

Встановлено, що у довоєнний період прибережні води Одеси характеризувалися відносною стабільністю показників та поступовим зниженням рівня евтрофікації, що відповідало середньому рівню трофності. Після початку повномасштабної війни зафіксовано порушення довоєнних тенденцій, зростання мінливості гідрохімічних показників і погіршення якості вод, зумовлене підвищенням надходження біогенних речовин, насамперед органічних форм азоту. Результати оцінки за комплексними показниками TRIX і EQR (BEAST) узгоджуються між собою та підтверджують перехід прибережних морських вод м. Одеса у 2024–2025 рр. до високого рівня трофності, що не відповідає доброму екологічному стану.

Результати дослідження свідчать про суттєвий вплив воєнних чинників, зокрема руйнування гідротехнічних споруд, зниження ефективності очисних систем та збільшення органічного навантаження з лиманних і річкових вод, на процеси евтрофікації прибережних вод м. Одеси. Отримані оцінки можуть бути використані для вдосконалення системи екологічного моніторингу та управління прибережними морськими водами в післявоєнний період. *Ключові слова:* евтрофікація, прибережні морські води, Чорне море, Одеса, біогенні речовини, TRIX, EQR (BEAST), воєнний вплив.



Problem statement. The problem of eutrophication of coastal marine waters is one of the most complex issues in the system of quality management of the Black Sea marine environment. Inputs of nutrients lead to disruption of trophic balance, excessive phytoplankton development, intensification of water “blooming” processes, reduced water transparency, oxygen depletion (formation of hypoxic and anoxic zones in the near-bottom layer), and ecosystem degradation. Under current conditions, traditional sources of eutrophication are supplemented by wartime factors, the impact of which on marine ecosystems remains insufficiently studied.

Relevance of the study. The relevance of this study is determined by the need to assess the ecological status of coastal waters under conditions of armed conflict and limited monitoring. Understanding the changes that have occurred since 2022 is critically important for predicting the future dynamics of eutrophication and for developing effective marine environment management measures.

Connection of the author’s work with significant scientific and practical tasks. The study was conducted within the framework of implementing the provisions of the EU Water Framework Directive [1] and the Marine Strategy Framework Directive [2, 3] aimed at achieving good ecological status of marine waters. The results obtained have practical significance for the national environmental monitoring system and for assessing the ecological consequences of wartime activities.

Analysis of recent research and publications. Previous studies have primarily addressed eutrophication of coastal waters in the north-western part of the Black Sea in the context of riverine runoff [4], urbanization [5-8], and climate change [9-12]. A large number of recent works have focused on the biogeochemical response of the north-western Black Sea to the breach of the Kakhovka HPP dam, using combined approaches that integrate satellite observations, hydrological modeling, and field measurements, e.g., [13, 14]. At the same time, the impact of wartime factors on nutrient loading and eutrophication patterns has been scarcely analyzed.

Identification of previously unresolved aspects of the overall problem. Insufficiently studied are the issues of the transformation of the ratio between mineral and organic forms of nutrients, as well as the sensitivity of complex water quality indicators to wartime factors.

Novelty. The novelty of the study lies in the quantitative assessment of changes in eutrophication of the coastal waters of Odesa before and after the onset of the full-scale war, using two independent complex indicators and analyzing the role of the organic component of nutrient loading.

Methodological or general scientific significance. The study demonstrates the feasibility of applying the complex indicators TRIX and EQR (BEAST) under conditions of limited monitoring and can be used as a methodological approach for assessing the ecological status of coastal marine waters in crisis situations.

Presentation of the main material.

Materials and Methods

The study was conducted for the coastal waters of the north-western part of the Black Sea within the recreational zone of the city of Odesa, corresponding to the coastal water body CW5 according to the Marine Conservation Strategy of Ukraine [15]. The analysis covers a seven-year period from 2019 to 2025, including the pre-war (2019–2021) and wartime (2022–2025) stages, which allowed for the assessment of transformations in eutrophication processes under the influence of changes in anthropogenic pressure.

The study was based on data from regular environmental monitoring of coastal waters conducted by the Ukrainian Scientific Center of Marine Ecology, with a weekly sampling frequency at fixed stations located in the areas of Arkadia Beach, Cape Malyyi Fontan, and the Odesa Yacht Club (Fig. 1). The work utilized results from hydrochemical and hydrobiological measurements. Eutrophication status was assessed using indicators of nutrient content (concentrations of mineral and total forms of nitrogen, phosphorus and Silicon (TP, P(PO₄), TN, N(NO₂), N(NO₃), N(NH₄), Si(SiO₄))), chlorophyll-a concentration (Chl-a), dissolved oxygen (DO), and supporting abiotic parameters such as biochemical oxygen demand (BOD) and pH.

The complex assessment of eutrophication and water quality was carried out using the TRIX trophic index [16-18], which combines indicators of chlorophyll-a concentration, deviation of oxygen saturation from 100%, concentrations of mineral forms of nitrogen, and total phosphorus. The TRIX index was calculated for each measurement set, followed by averaging across temporal and spatial scales, allowing for the determination of intra-annual and inter-annual variability of trophic status in the coastal waters.

Additionally, the BEAST (HEAT-3.0) methodology [19, 20], recommended for the Black Sea area, was applied to assess the ecological status of marine waters. Within this approach, the dimensionless water quality ratio (EQR) was determined based on the ratio of observed indicator values to target values corresponding to good ecological status. The calculations included groups of indicators for inorganic forms of nitrogen and phosphorus, primary production (chlorophyll-a), and oxygen regime. The final assessment of eutrophication level was determined by the highest complex EQR value within the respective indicator groups.

Statistical analysis methods were applied to identify long-term changes and to perform a comparative analysis of the pre-war and wartime periods. The results obtained were used to interpret the impact of wartime factors on eutrophication processes in the coastal waters of Odesa.

Changes in abiotic parameters

Analysis of abiotic parameters indicates a significant change in the hydrochemical regime of the coastal waters of Odesa after 2022 (Fig. 2).



Fig. 1. Location of monitoring stations in the coastal waters of Odesa

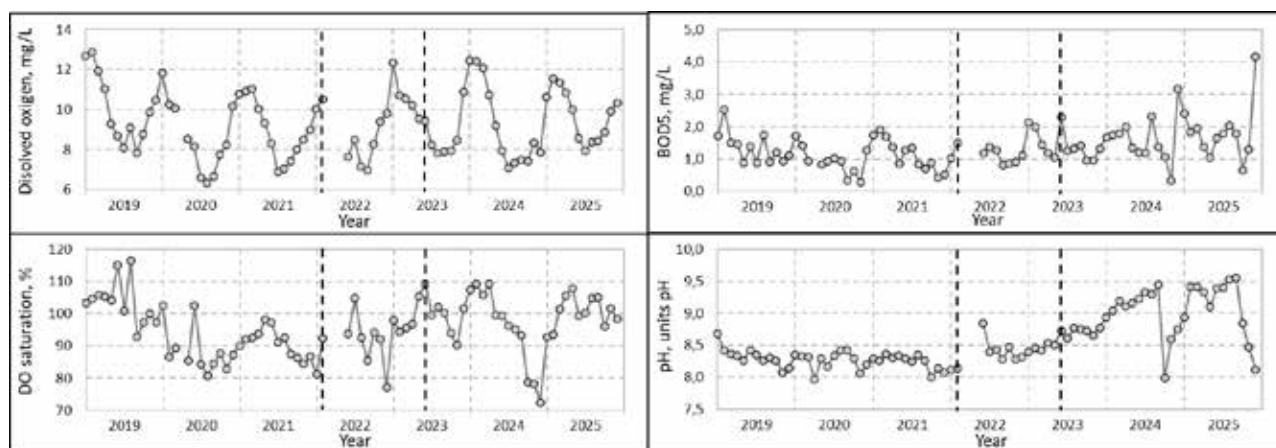


Fig. 2. Variability of monthly mean values of abiotic parameters

Note: Here and below, vertical lines indicate the onset of the full-scale war and the Kakhovka HPP disaster.

The oxygen regime of the coastal waters in 2019–2025 was characterized by relative stability and corresponded to good ecological status. Dissolved oxygen concentrations ranged from 4.0 mg/L to 15.7 mg/L (saturation from 35.0 % to 154.6 %). Annual mean values were 8.6–10.0 mg/L (saturation 88.8–104.0 %). Episodes of decreased oxygen content and saturation to critical levels were episodic and mostly occurred during the warm season. The lowest values were recorded at

the end of 2024 and 2025 (4.0 mg/L, 35.0 % saturation, and 4.1 mg/L, 51.6 % saturation, respectively), indicating episodic oxygen depletion events superimposed on generally well-oxygenated conditions. This is consistent with the tendency of the north-western shelf to short-term hypoxia under certain stratification conditions [21].

During the pre-war period, biochemical oxygen demand (BOD_5) was characterized by moderate values typical for coastal waters with a medium trophic status.

In the wartime period, an increase in the frequency of exceedances of the maximum allowable BOD₅ value (3.0 mg/L) was observed, particularly in 2024–2025, indicating an increase in organic loading on the coastal waters.

Changes in pH also indicate a disruption of pre-war stability. During 2019–2021, average pH values mostly remained within the normative range for marine waters (6.5–8.5 pH units). In 2023–2025, a systematic increase in pH was observed, with frequent exceedances of the maximum allowable level (8.5 pH units), serving as an indirect indicator of intensified photosynthetic activity and water “blooming.” At the same time, a minimum pH value of 6.28 was recorded in 2024, indicating a short-term episode of water acidification against the background of overall increased alkalinity.

Dynamics of nutrients and chlorophyll-a

The most pronounced changes in the hydrochemical regime of the coastal waters of Odesa after 2022 are observed in nutrient indicators (Fig. 3).

During the pre-war period, concentrations of phosphate and total phosphorus in the coastal waters of Odesa showed a tendency toward stabilization or gradual decline, consistent with long-term trends observed in the early 21st century [11, 12]. Annual mean phosphate phosphorus values (10.7–19.2 µg/L) corresponded to good ecological status, while elevated concentrations

were seasonal and mostly recorded in the autumn–winter period. After 2022, the variability pattern of phosphorus changed. Although annual mean phosphate phosphorus values in 2023–2025 generally remained close to pre-war levels, the frequency of high total phosphorus concentrations, corresponding to moderate and poor ecological statuses, increased. This indicates a rise in the proportion of the organic component of phosphorus in the overall nutrient balance. Overall, phosphate phosphorus values ranged from <0.5 to 113 µg/L, while total phosphorus ranged from 7 to 716 µg/L.

The most pronounced changes were recorded for nitrogen compounds. In 2019–2021, the total content of mineral forms of nitrogen was characterized by relative stability and a gradual decreasing trend, consistent with long-term patterns [11, 12]. In contrast, during the wartime period, concentrations of both mineral nitrogen forms and total nitrogen sharply increased. Nitrite nitrogen ranged from <0.5 to 24.2 µg/L, nitrate nitrogen from <5 to 1,995 µg/L, ammonium nitrogen from <15 to 245 µg/L, and total nitrogen from 97 to 72,628 µg/L. Particularly notable is the anomalous increase in total nitrogen in 2024–2025, largely due to a rise in its organic component.

The ratio of organic to mineral forms of nitrogen and phosphorus changed significantly after 2022 (Fig. 4). During the pre-war period, mineral forms of nitrogen,

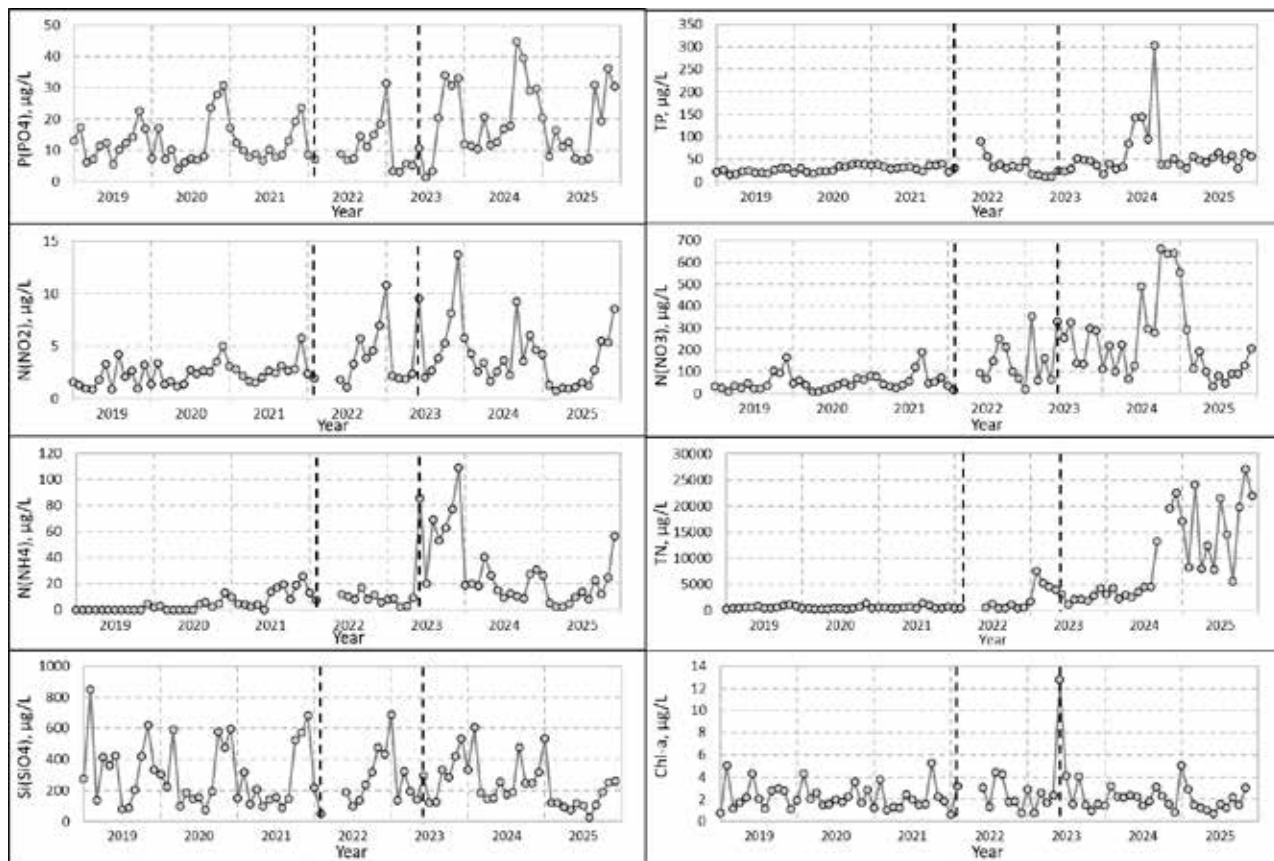


Fig. 3. Variability of monthly mean values of nutrients and chlorophyll-a

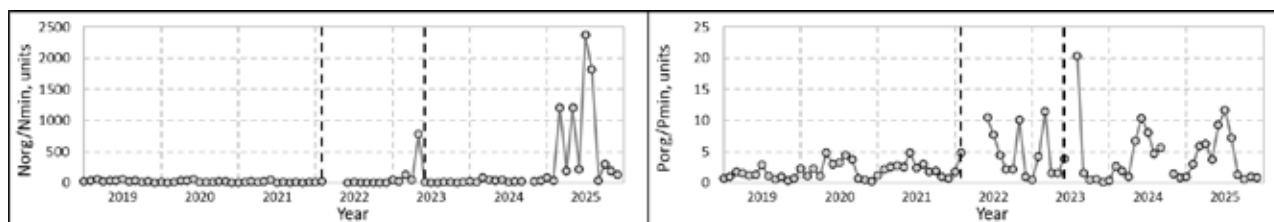


Fig. 4. Monthly dynamics of the ratios of organic to mineral forms of nitrogen and phosphorus

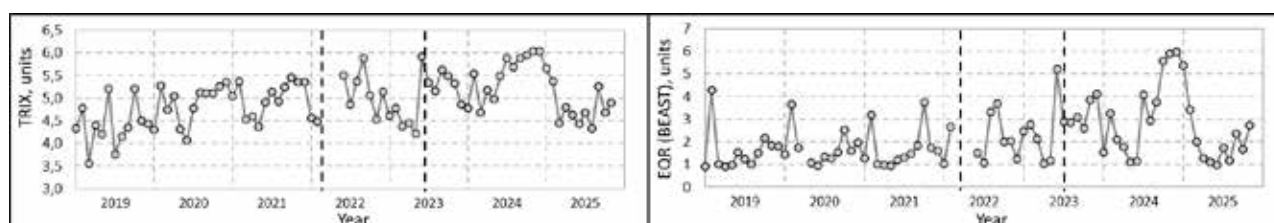


Fig. 5. Monthly dynamics of the complex indicators TRIX and EQR

typical of controlled anthropogenic influence, predominated. In the wartime period, however, the role of organic forms sharply increased, coming from estuarine and riverine waters, as well as due to disruption of wastewater treatment system functioning.

Silicon ($\text{Si}(\text{SiO}_4)$) concentrations in the coastal waters of Odesa ranged from <10 to $2,465 \mu\text{g/L}$. Annual mean values for 2019–2025 were 149 – $344 \mu\text{g/L}$ and showed a decreasing trend, which to some extent limits the development of diatom algae.

No pronounced changes in chlorophyll-*a* concentrations were observed in the coastal zone of Odesa throughout the study period. Changes in chlorophyll-*a*, as an indicator of phytoplankton biomass, reflect variations in the ecological status of the aquatic environment. Overall, this dynamics corresponds to the characteristic seasonal pattern of the north-western shelf. Peaks in chlorophyll-*a* concentrations were usually observed in spring and summer, associated with increased phytoplankton photosynthetic activity under elevated temperatures and enhanced riverine nutrient input. During other seasons, particularly autumn and winter, chlorophyll-*a* levels remained consistently low, generally not exceeding 2 – $5 \mu\text{g/L}$. The maximum chlorophyll-*a* value recorded during the entire observation period was $35 \mu\text{g/L}$ at the beginning of June 2023, which was linked to the Kakhovka HPP disaster.

Assessment of eutrophication in coastal waters using complex indicators TRIX and EQR (BEAST)

Calculations of the TRIX trophic index and the EQR (BEAST) water quality indicator allowed for the synthesis of hydrochemical and hydrobiological observations and the identification of changes in the degree of eutrophication over the study period.

Before the onset of the full-scale war, annual mean TRIX values in the coastal waters of Odesa ranged from 4.4 to 5.0 , corresponding to the border between moder-

ate and high trophic status, with water quality assessed as good or moderate. After the war began, TRIX values increased to 5.0 – 5.4 , corresponding to high trophic status (moderate water quality). Intra-annual fluctuations of the index were moderate and exhibited a clearly defined seasonal pattern (Fig. 5).

The assessment results using the BEAST methodology complement and confirm the conclusions obtained based on the TRIX index. During the pre-war period, annual mean EQR values of 1.6 – 1.8 in the coastal waters of Odesa corresponded to a moderate ecological status, while in the wartime period they indicated poor status, ranging from 2.1 to 3.1 . Maximum EQR values were recorded during periods of increased nutrient loading and intense water “blooming,” consistent with hydrochemical observations.

The observed changes in TRIX and EQR (BEAST) indicators are well aligned with the dynamics of nutrient concentrations and indicate relative stability of the coastal ecosystem prior to the onset of the full-scale war. After the war began, the annual mean values of both indicators no longer corresponded to good ecological status, reflecting an overall deterioration in the quality of coastal waters.

Main conclusions. During the wartime period, a significant deterioration of the ecological status of the coastal waters of Odesa was observed, driven by increased organic nutrient loading and disruption of the oxygen regime. The most pronounced changes were recorded for total nitrogen and its organic component, confirming the informativeness of this indicator for assessing the impact of wartime factors. The application of two independent integrated assessment methods, TRIX and EQR (BEAST), allowed for a consistent evaluation of eutrophication processes and confirmed a substantial decline in the condition of coastal waters during the wartime period compared to the pre-war

stage. The observed changes in these indicators are well aligned with nutrient dynamics and indicate relative stability of the coastal ecosystem prior to the onset of the full-scale war.

Prospects for the application of the study results. The results obtained can be used to improve marine water monitoring systems, develop adaptive measures in the post-war period, and assess ecological risks for coastal areas.

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