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Prevention of contamination of the Southern Bug River with nitrogen compounds using constructed wetlands

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Abstract. The purpose of the study was to investigate trends in the pollution of the Southern Bug River with nitrogen compounds and to analyse the use of constructed wetlands to prevent this pollution. Statistical processing of the results of measurements of nitrogen-containing compounds was carried out according to open data of the State Agency for Water Resources of Ukraine and environmental risks were assessed. Using STATISTICA 12 and proprietary Python software, the authors created charts of the scale of ammonium ions and nitrate ions. The risks of exceeding the maximum permissible concentration for all observation posts for these indicators were estimated. Significant exceedances of maximum permissible levels of nitrogen compounds were detected, particularly downstream of Khmelnytskyi. Due to the self-cleaning processes occurring in the river, the levels of nitrogen-containing compounds decreased to acceptable values when measured at the drinking water intake in Vinnytsia, but simultaneously, the concentration of phytoplankton increased significantly. Correlations between pollution parameters were investigated and scatter plots were obtained.

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The results of the study are of practical value for monitoring and managing water quality in the Southern Bug River basin. Due to long-term statistical analysis, the study identified spatiotemporal trends in river pollution with nitrogen-containing compounds, which are key factors of eutrophication of water bodies. As an effective and economically feasible solution to the problem, the study proposed the introduction of constructed wetlands (CWs) and considered in detail two main types of CW – with free water surface and subsurface flow – their design features and cleaning mechanisms. CWs are a promising, decentralised technology for wastewater treatment in small communities that provides significant advantages over conventional systems due to their low cost, ease of operation, and environmental sustainability

Keywords: water; eutrophication; ammonium ions; nitrate ions; pollution trend; purification; wetlands

Introduction

The Southern Bug is one of the largest rivers in Ukraine, with its entire catchment area located within the country's borders. High regulation, a developed agricultural sector, a number of large cities, energy facilities, and industry cause a significant anthropogenic load on the river, which is primarily expressed in the enrichment of water with nutrients, in particular, nitrogen compounds (Bonchkovsky & Osadcha, 2024; Bonchkovsky & Osypov, 2024). To determine trends in the quality parameters of the Southern Bug River, it is considered appropriate to use remote sensing methods, in particular, using satellites of the European Space Agency and NASA. Information from artificial satellites provides data on the deterioration of the quality of water bodies, mass flowering of phytoplankton, overgrowth of water bodies with certain species of higher aquatic plants (Shevchuk *et al.*, 2019; Vyshnevskyi, 2019). In order to determine the cause of these phenomena, it is necessary to compare them with the results of on-site parameter measurements, which are available, in particular, on open resources. As stated by I. Nezbrytska *et al.* (2024), similar problems associated with nitrogen pollution are typical for other Ukrainian rivers. The relevance of the topic is conditioned by the need to increase the reliability of assessing anthropogenic impact on water bodies and develop appropriate methods and means to reduce it.

According to V. Khilchevskyi *et al.* (2025), the deterioration of water quality in water bodies due to contamination with nitrogenous compounds requires the search for new ways to use cost-effective water treatment methods. Constructed wetlands (CWs) are a natural and cost-effective process for cleaning and improving water quality and reducing overall eutrophication (Semeniaka *et al.*, 2022). The restoration and protection of wetlands is protected by the Ramsar Convention on Wetlands (1971), because in addition to the purifying function, wetlands are particularly important for the conservation of biodiversity. Constructed wetlands have been used since the 1950s and provide better treatment for various types of wastewater, such as urban wastewater, municipal wastewater, industrial wastewater, and agricultural waste, while mimicking the biological, physical, and chemical processes that occur in natural wetlands (Khaietsky, 2022). The use of constructed wetlands for wastewater treatment has increased dramatically in recent years. According to S. Kataki *et al.* (2020), CW is considered an ecological system to replace conventional secondary and tertiary municipal and industrial wastewater treatment processes. Wastewater treatment plants have replaced conventional wastewater treatment processes and created a reliable treatment system based on a complex natural ecosystem (Muduli, *et al.*, 2023). Wetlands as an unconventional wastewater treatment technology have great potential in developing countries, which provides some advantage over conventional mechanised treatment processes and is economically feasible.

The purpose of the study was to analyse trends in the pollution of the Southern Bug River with nitrogen-containing compounds and to propose mechanisms for preventing such pollution using constructed wetlands.

Materials and Methods

The study was comprehensive in nature and combined analysis of empirical data with theoretical generalisation for a comprehensive investgation of the problem of pollution of the Southern Bug River and the search for ways to solve it. The methodological base of the study included the collection and processing of primary data, their statistical analysis, and analysis of scientific literature. The object of research was the hydroecological state of the upper reaches of the Southern Bug River. The subject of the study was the dynamics of the content of nitrogen-containing compounds (ammonium ions and nitrate ions) in water and methods for their reduction. The main material for the analysis was official surface water quality monitoring data obtained from the State Agency of Water Resources of Ukraine (2025). Time series of data for the period from January 1, 2000 to April 20, 2024 were analysed. The analysis was performed for six observation posts (OPs) located in the upper reaches of the river to the drinking water intake of Vinnytsia, which allowed tracking the dynamics of pollution along the river. To assess environmental risks, the maximum permissible concentrations (MPC) established by state sanitary standards for fishery water bodies and drinking water supply sources were used.

Processing of numerical data from observation posts was carried out using the STATISTICA 12 statistical analysis package and proprietary software developed in the Python programming language. The choice of these tools was justified by their extensive capabilities for processing large amounts of data and flexibility in visualising results. The distribution was checked for normality using the Kolmogorov-Smirnov and Lilliefors criteria. The goal was to determine whether the distribution of data corresponds to the normal law. This is a mandatory step, since it determines the choice of further analysis methods (parametric or nonparametric). Histograms and box-whisker plots were constructed to visualise and analyse data that did not obey the normal distribution law. Histograms were used to visually evaluate the shape of the distribution of indicators. Span diagrams were chosen as the main tool for comparing data between different years and posts, as they clearly demonstrate the median, interquartile span, and outliers that are more resistant to extreme values than the arithmetic mean. Scatter plots were constructed and the Pearson correlation coefficient (r) was calculated to identify and quantify the statistical relationship between various water quality indicators (in particular, between ammonium ions and nitrate ions). This allowed testing hypotheses about common sources of origin of pollutants.

Results and Discussion

The object of analysis is monitoring data from observation posts (OPs) in the upper reaches of the Southern Bug River to the drinking water intake in Vinnytsia (Table 1). Data from 2000-2024 were processed by the State Agency of Water Resources of Ukraine (2025). The online system automatically generates a graph of changes in indicators for the required period, but it is not very informative due to the presence of a random component of changes in the parameters under study.

Table 1. Observation posts in the upper reaches of the Southern Bug

No.	Full title of the observation post
1	Southern Bug River, 744 km, Kopystin village, downstream of Khmelnytskyi
2	Southern Bug River, 711 km, Medzhibizh urban-type settlement, Medzhibizh reservoir
3	Southern Bug River, 692 km, Shchedrove village, Shchedrove reservoir
4	Southern Bug River, 652 km, Khmilnyk city, drinking water intake, upstream of the city
5	Southern Bug River, 607 km, Gushchyntsi, downstream of the village, drinking water intake, Kalynivka city
6	Southern Bug River, 582 km, Vinnytsia city, Sabariv reservoir, drinking water intake of the city, upstream of the city

Source: created by the State Agency of Water Resources of Ukraine (2025)

To assess general trends in changes in water quality parameters, they had to be processed using statistical methods. Using STATISTICA 12 and proprietary Python software, span charts and histograms for ammonium ions and nitrate ions were created. The programme developed by the authors builds box-whisker plots for each of the years of observation for all the parameters under study based on tabular data (State Agency of..., 2025). The Kolmogorov-Smirnov and Lilliefors criteria were applied to verify compliance with the normal distribution law. The risk was assessed on a scale from 0 to 1. The histogram for the ammonium ion index is shown in Figure 1.

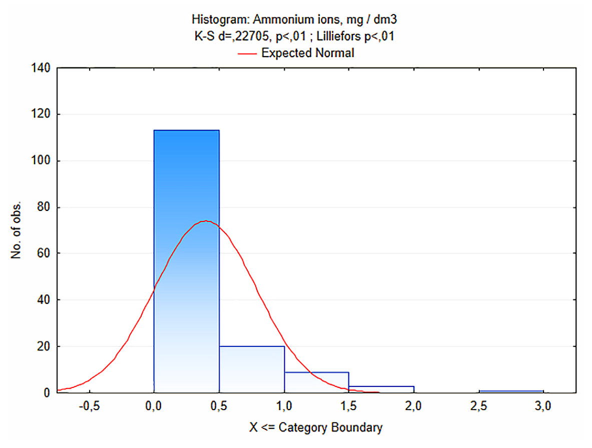
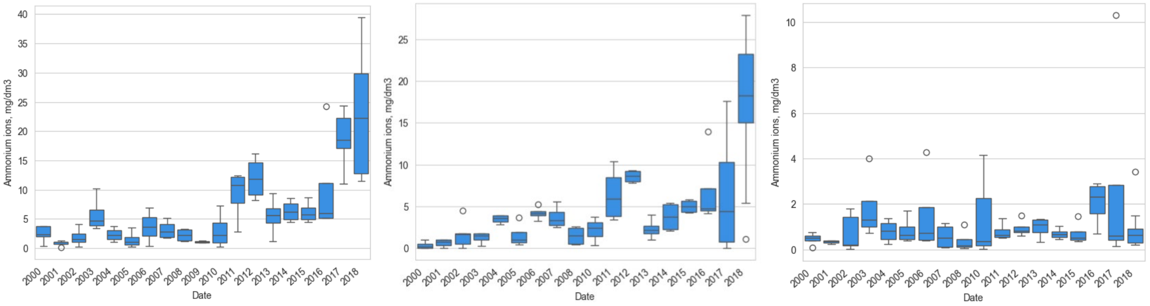


Figure 1. Histogram for ammonium ions, mg/dm^3
Source: created by the State Agency of Water Resources of Ukraine (2025)

This histogram shows that in this case, both by the form of the histogram and by the Kolmogorov-Smirnov criteria ($p < 0.01$) and Lilliefors ($p < 0.01$), the distribution law differs from the normal one. The same results were obtained for the remaining indicators under study. Therefore, for further data processing and constructing a span diagram, the values of the median and interquartile span were used. Risk of exceeding the maximum permissible concentration (MPC) for water bodies in terms of ammonium ions (2 mg/dm^3) was large for all years of observations (Fig. 2).

For the use of this water as drinking water, the standard of facilities for the ammonium ion indicator is 0.5 mg/dm^3, however, the water at this intake point exceeds the specified standard for most years of observations, which makes it necessary to use special physico-chemical methods for its purification. There is a significant multiple excess of the maximum permissible concentration for this indicator in the upper reaches of the Southern Bug, and a gradual deterioration in water quality since 2000. Due to self-purification processes occurring in the middle reaches of the river, the ammonium ion concentration decreases to acceptable levels. Risk of exceeding the MPC for water bodies in terms of nitrate ions (10.0 mg/dm^3) is also present to a certain extent, since for 24 years of observations (2000-2024,) at the observation post No. 6 (Southern Bug River, 582 km, Vinnytsia, Sabariv reservoir, drinking water in and out of the city, upstream of the city) this indicator exceeded the maximum permissible concentration in three of them, in particular, in 2013, 2014, and 2021 (Fig. 3).

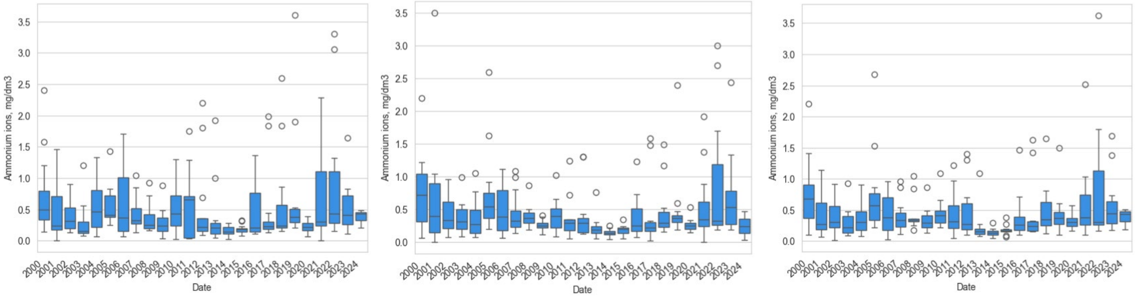
The scattering diagram for the indicators of ammonium ions and nitrate ions when processing data from 2010 to 2022 at OP No. 6 is shown in Fig. 4.



OP No. 1 Southern Bug River, 744 km, Kopystyn village, downstream of Khmelnytskyi city

OP No. 2 Southern Bug River, 711 km, Medzhibizh urban-type settlement, Medzhibizh reservoir

OP No. 3 Southern Bug River, 692 km, Shchedrove village, Shchedrove reservoir

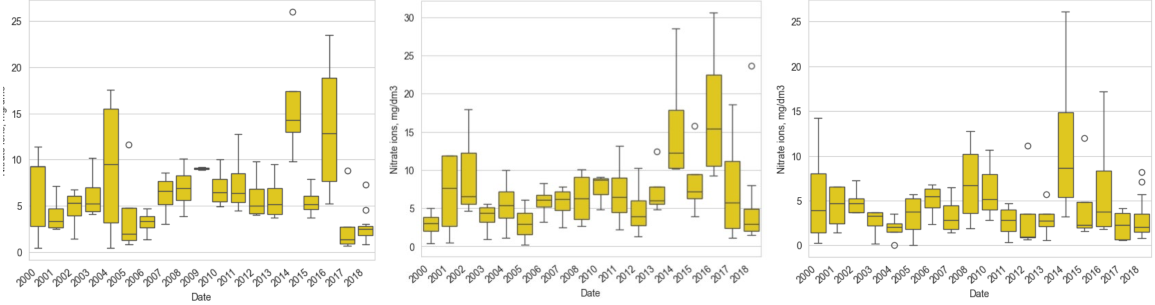


OP No. 4 Southern Bug River, 652 km, Khmilnyk city, drinking water intake, upstream of the city

OP No. 5 Southern Bug River, 607 km, Gushchintsi village, downstream of the village, drinking water intake, Kalynivka city

OP No. 6 Southern Bug River, 582 km, Vinnytsia city, Sabariv reservoir, drinking water intake of the city, upstream of the city

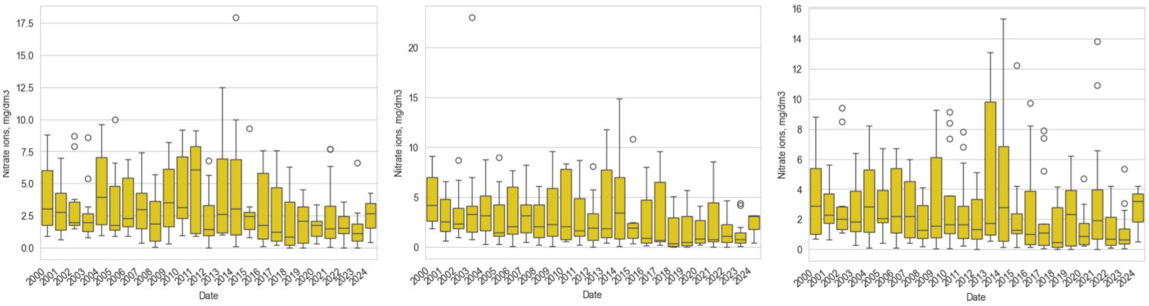
Figure 2. Span diagrams for the ammonium ions indicator in the upper reaches of the Southern Bug River
Source: created by the State Agency of Water Resources of Ukraine (2025)



OP No. 1 Southern Bug River, 744 km, Kopystyn village, downstream of Khmelnytskyi city

OP No. 2 Southern Bug River, 711 km, Medzhibizh urban-type settlement, Medzhibizh reservoir

OP No. 3 Southern Bug River, 692 km, Shchedrove village, Shchedrove reservoir



OP No. 4 Southern Bug River, 652 km, Khmilnyk city, drinking water intake, upstream of the city

OP No. 5 Southern Bug River, 607 km, Gushchintsi village, downstream of the village, drinking water intake, Kalynivka city

OP No. 6 Southern Bug River, 582 km, Vinnytsia city, Sabariv reservoir, drinking water intake of the city, upstream of the city

Figure 3. Span diagrams for the nitrate ion indicator in the upper reaches of the Southern Bug River
Source: created by the State Agency of Water Resources of Ukraine (2025)

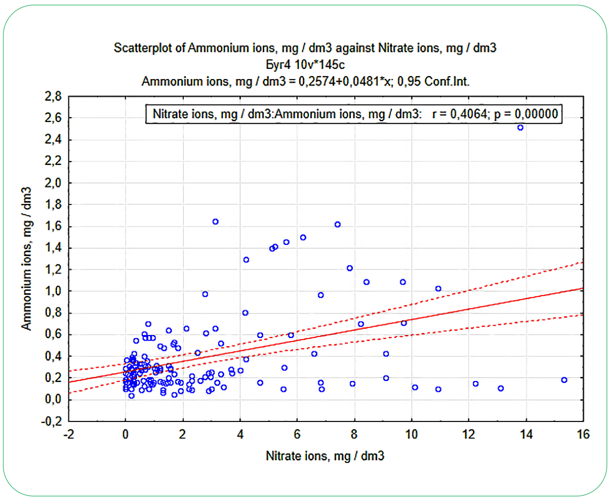


Figure 4. Scatter plot for ammonium ion and nitrate ion data from 2010 to 2022

Source: created by the State Agency of Water Resources of Ukraine (2025)

Since a regression coefficient is obtained for linear regression of the ammonium ion and nitrate ion indicators $r = 0.41$, then this indicates the presence of a weak relationship between the specified parameters. Since $r < 0.7$, then the presence of this bond can be ignored and the weakly correlated change in the parameters of ammonium ions and nitrate ions can be explained by the influence of other additional factors. In addition, correlation analysis revealed the presence of a weak relationship between parameters such as nitrate ions and nitrite ions (regression coefficient $r = 0.26$) and dissolved oxygen and biochemical oxygen consumption ($r = 0.21$).

Given the excessive pollution in the upper reaches of the Southern Bug River, natural mechanisms for cleaning waters contaminated with nitrogen-containing compounds should be used, in particular, constructed wetlands (CWs). CWs are classified according to various parameters. The most significant features are the water runoff regime (surface and subsurface) and the type of macrophyte growth (in the form of fixed floating, submerged, free-floating, and air-aquatic plants) (Dong & Kuang, 2024). The quality of final drains from the systems improves along with the complexity and improvement of the system. Two common types of constructed wetlands commonly created for wastewater treatment are free water surface wetlands (FWS) and subsurface flow wetlands (SF) (Santos *et al.*, 2024).

A wetland with a free water surface (FWS) consists of a shallow basin, soil or other environment to support vegetation roots, and a water-regulating structure that maintains a shallow water depth. Cork flow conditions are achieved in FWS by maintaining a shallow water depth, low water flow rate, and the presence of plant stems and bedding to regulate water flow, especially in long and narrow channels (Ilyas & van Hullebusch, 2020). Wetlands created by surface streams mimic natural wetlands, where water flows upstream of the Earth's surface and flows through wetlands at an average depth of 15 to 30 cm (Fig. 5).

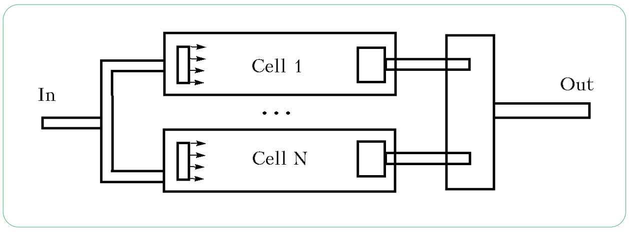


Figure 5. Diagram of a constructed wetland with a free water surface

Source: compiled by the authors

Wetlands with FWS can provide wildlife habitat, aesthetic benefits, and an ideal water treatment process. In FWS wetlands, aerobic conditions dominate near the surface layer, while deeper layers, water, and substrate usually operate in an anaerobic mode. In many systems, the efficiency of removal is affected by the proportional ratio of the intake of concentrations. In FWS, constructed wetlands have wastewater with low concentrations of organic matter and suspended solids. M. Khajah *et al.* (2023) reported that the efficiency of nitrogen and phosphorus removal varies greatly and reaches 50%. In addition, the effectiveness of removing faecal coliforms varies and can be up to two times. A potential plan might be a cell with an open water zone for initial solid sedimentation to promote flocculation and separation of solids, then a floating vegetation zone with a two-day retention at maximum runoff, then an open water zone with a two-day retention, and then a floating vegetation zone with a two-day retention.

Wetlands built with FWS were designed with an aspect ratio (which is the length: width ratio) of less than 1:1 to more than 90:1, but most of the recommended and optimal ratios were in the range of 3:1 to 5:1. Approximately 15 cm of soil was laid on top of the liner to support vegetation. Marsh plants can be grown by sowing or transplanting. Maintenance of FWS wetlands can be cheap and simple, it includes periodic burning of vegetation on wetlands to treat, monitor and regulate the height of the water surface, keeping the inlet and outlet structures of wetlands free of debris, filtering and removing sediment if necessary.

The first pilot subsurface flow wetland (SF) was developed in the 1950s in Germany. Constructed wetlands with subsurface runoff can be classified according to the direction of water flow, horizontal or vertical (Vymazal *et al.*, 2021). SF wetlands include a sealed pool with a porous rock or gravel substrate, vegetation, and release control system, and they can also contain up to 4 m of gravel, and the water surface level is kept downstream of the top surface of the gravel. The flow path in wetlands constructed according to SF is horizontal, whereas in some systems vertical flow paths can be found (Fig. 6). Generally, it is necessary to plant seedlings of higher aquatic plants in SF wetlands, as the gravel substrate is often not suitable and favourable for seed germination and rooting (Nouri Goukeh & Alamdari, 2024).

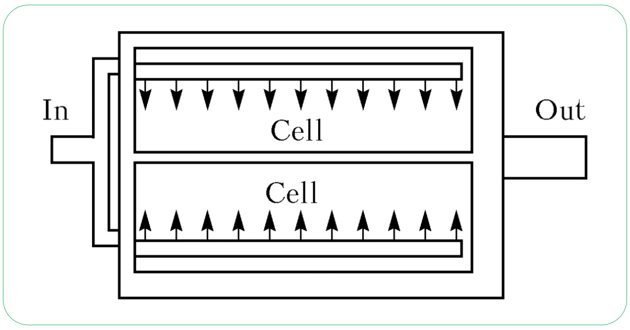


Figure 6. Diagram of a constructed wetland of a subsurface flow

Source: compiled by the authors

According to M. Ali *et al.* (2024), organic compounds decompose aerobically and anaerobically by bacteria attached to underground plant roots and the surface of a medium that mimics surface runoff, as in a conventional biological treatment process. However, oxygenation of the rhizosphere of constructed wetlands is insufficient, and therefore, incomplete nitrification is the main reason for limited nitrogen removal, which can reach 50% at best. As noted by D. Yao *et al.* (2023), evapouration, adsorption, and uptake by plants in constructed wetlands play a minor role in nitrogen removal. Therefore, phosphorus removal occurred through ligand exchange reactions. A brief description of the mechanism is that phosphate can displace water or a hydroxyl group from the surface of aqueous iron and aluminium oxides. Removal of microbial contamination is mainly carried out through a combination of physical, chemical, and biological processes and factors (Tang *et al.*, 2020). However, due to the difference in hydraulic gradient requirements, the aspect ratio (L:W) was recommended to be relatively low (in the range of 0.4:1 to 3:1) to provide flexibility and margin potential for future operational adjustments and upgrades.

Wetlands constructed using SF system are best suited for wastewater treatment with relatively low solid concentrations and relatively uniform flow conditions due to hydraulic constraints imposed by the substrate. The wetland water treatment property uses the relationships between certain plants and vegetation macrophages, micro-organisms, and soil in a systematic process. This depends on factors such as the natural context, local climate, project design, plant types, and microbial functions. According to T. Fedoniuk *et al.* (2022), during the treatment process, plant macrophages absorb various pollutants from wastewater, accumulating them in their tissues. It maintains a suitable environment for the growth of microorganisms that play a significant role in removing pollutants. In addition, the roots of plant macrophages carry oxygen through the water, improving the aerobic conditions necessary for the purification process. As a result of these combined processes, wastewater quality is improved to meet water reuse standards.

Conclusions

Remote sensing of the Southern Bug River in the visible and near-infrared ranges helped to identify the deterioration of the quality of water bodies, mass flowering of phytoplankton, and overgrowth of water bodies with certain species of higher aquatic plants over time. In order to determine the cause of these phenomena, they were compared with the results of on-site parameter measurements obtained from open resources of the State Water Resources Agency of Ukraine. According to the measurement results, a significant excess of indicators for nitrogen-containing compounds in the upper reaches of the Southern Bug was revealed, which obviously led to the phenomena of mass flowering of phytoplankton and the development of higher aquatic plants. Statistical processing of the results of measurements of nitrogen-containing compounds was carried out according to open data of the State Agency for Water Resources of Ukraine and environmental risks were assessed. The detection of exceedances of maximum permissible concentrations downstream of Khmelnytskyi helped to localise problem areas requiring environmental intervention, in particular, the regulation of wastewater discharges. The established correlation between the content of nitrogen-containing compounds and phytoplankton biomass allowed the authors to confirm the hypothesis of a causal relationship between pollution and mass "flowering" of water. To solve the problem of pollution of the Southern Bug River with nitrogen compounds, it is worth using artificial wetlands, which have great potential for effective treatment and management of wastewater in rural areas.

When properly designed and operated, constructed wetlands have great advantages over conventional wastewater treatment systems due to their relatively low cost, ease of operation and maintenance. CW is given the opportunity to provide small communities with their own wastewater treatment systems. However, such communities usually do not have effective wastewater treatment systems and are not connected to centralised sewage systems. In general, the use of CWs allows creating a decentralised wastewater treatment system that is less vulnerable to emergencies both during military operations and in peacetime.

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Conflict of Interest

None.

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Запобігання забрудненню р. Південний Буг нітрогеновмісними сполуками з використанням штучних водно-болотних угідь

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Анотація. Метою дослідження було дослідити тенденції зміни забруднення р. Південний Буг нітрогенвмісними сполуками та проаналізувати використання штучних водно-болотних угідь для запобігання цього забруднення. Було проведено статистичну обробку результатів вимірювань нітрогенвмісних сполук за відкритими даними Державного агентства водних ресурсів України та оцінено екологічні ризики. За допомогою програми STATISTICA 12 та власного програмного забезпечення на мові Python було створено діаграми розмаху за показниками амоній-іонів та нітрат-іонів. Оцінено ризики перевищення гранично допустимої концентрації для всіх постів спостереження за вказаними показниками. Виявлено значні перевищення гранично допустимих рівнів нітрогенвмісними сполуками, зокрема, нижче м. Хмельницький. За рахунок процесів самоочищення, що відбуваються у річці показники рівнів нітрогенвмісних сполук зменшується до допустимих значень при вимірюваннях у питному водозаборі м. Вінниця, однак при цьому суттєво зростає концентрація фітопланктону. Досліджено кореляційні зв'язки між параметрами забруднення та отримано діаграми розсіювання. Результати дослідження мають практичну цінність для моніторингу та управління якістю води в басейні річки Південний Буг. Завдяки довгостроковому статистичному аналізу дослідження дозволяє виявити просторово-часові тенденції забруднення річки нітрогенвмісними сполуками, що є ключовими чинниками евтрофікації водойм. Як ефективне та економічно доцільне рішення проблеми, у статті було запропоноване впровадження штучних водно-болотних угідь (ШВБУ) та детально розглянуто два основні типи ШВБУ – з вільним поверхневим потоком та підповерхневим потоком – їхні конструктивні особливості та механізми очищення. ШВБУ є перспективною, децентралізованою технологією для очищення стічних вод у невеликих громадах, яка забезпечує значні переваги перед традиційними системами завдяки низькій вартості, простоті експлуатації та екологічній стійкості

Ключові слова: вода; евтрофікація; амоній-іони; нітрат-іони; тренд забруднення; очищення; болота