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Environmental assessment of the impact of hydrocarbon pollution on the condition of cooling ponds

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✓ **Abstract.** Hydrocarbon pollution remains an important and unresolved problem that has worsened during a full-scale invasion, in particular due to the ingress of rocket debris with a significant amount of petroleum products into surface waters. The aim of the work was to provide an assessment of the ecological state of a water body exposed to hydrocarbon and other uncharacteristic pollutants. Field methods: 5 water samples were taken to determine the content of petroleum products and the pH value, and 5 water samples were taken to determine the physical properties, main ions, and heavy metal content. Laboratory and instrumental methods: titrimetric – used to determine the content of chlorides, alkalinity, hardness. According to the results of studies, it was found that chloride ions were in the range of 264-274 mg/dm³, alkalinity values – 3.6-5.5 mmol/dm³. As a result of the hardness study, it was found that the waters are soft. The content of nitrites was determined by photocolometric method (their traces were recorded). Measurement: the pH value was determined by the electrometric method. According to the results, the water was classified as neutral and slightly alkaline. The content of petroleum products in the range of 0.19-16.36 mg/dm³ was determined by fluorimetry (exceeding the standard by 54.5 times). The content of cadmium, zinc, manganese, copper, chromium, and ferric iron was determined by modulation polarisation spectrophotometry. The content of chromium, cadmium, copper was in the range of 0.001 mg/dm³, manganese content – from 0.001 mg/dm³ up to 0.004 mg/dm³, zinc content – from 0.004 mg/dm³ up to 0.008 mg/dm³, ferum content – from 0.004 mg/dm³ up to 0.02 mg/dm³. Using the Ruffel method, the total dilution factor of wastewater in the reservoir was determined to be 125.24. According to the method of calculating the amount of compensation for losses, the damage caused by hydrocarbon pollution was determined, which is 143 thousand UAH. The practical value of the work lies in improving scientific and practical approaches to determining the strategy for conducting a comprehensive environmental study of the state of multifunctional artificial water bodies

✓ **Keywords:** oil products; reservoir; environmental regulations; environmental condition; water dilution ratio; economic losses

✓ Introduction

Hydrocarbon pollution is one of the most common and dangerous pollutants in water bodies. Their ingress with untreated wastewater and stormwater requires detailed

analysis, identification of factors, and research into self-purification processes. The problem was exacerbated during the full-scale invasion due to drones hitting oil depots,

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spills and oil products entering water bodies, broken military equipment in water bodies, wreckage of downed missiles with a significant amount of unproduced fuel and oil products, and many other facts. The global scientific community has been focusing its research on creating a management and decision-making strategy in the context of sustainable development in the field of oil pollution for a long time. According to the latest global research, the main postulates of the impact of oil products on surface waters have been identified.

The research of O. Kratko *et al.* (2023) found that various types of water pollution are observed during missile launches. The discharge of biogenic compounds into water bodies leads to blooms and eutrophication of water bodies, a decrease in the level of oxygen saturation, an increase in the content of biogenic and organic substances, an increase in water turbidity, contamination with pathogenic microorganisms, and as a result, a threatening effect on aquatic life and human health. According to the researcher V. Hryniuk (2021), the processes of self-purification of natural watercourses from oil pollution depend on the flow rate (which increases the rate of mixing of water masses) and an increase in water temperature, which accelerates biochemical processes in a natural watercourse. Scientists R. Yang *et al.* (2023) concluded that rapid microbial decomposition of oil components was observed in river water during the day, and the rate of decomposition depends on the presence and functioning of the components of bacterial and fungal communities that utilise oil products.

Oil products are usually not found in natural waters. In uncontaminated lake waters (reservoir waters), the content of petroleum products is tenths or hundredths of a milligram per dm^3 (from 0.1 to 0.2 mg/dm^3 , sometimes up to 1.5 mg/dm^3). Hydrochemical studies of the state of water bodies analyse the hydrocarbon fraction, namely aliphatic, aromatic and other hydrocarbons, which make up about 80% of the total of all substances that make up oil and oil products. O. Biedunkova *et al.* (2024) concluded that a high degree of self-purification was characteristic of chlorides, ammonium nitrogen, and phosphorus phosphate; nitrite nitrogen, nitrate nitrogen, BOD₅, and COD had an average degree of self-purification; the lowest degree of self-purification of the river's surface waters was found for suspended solids, dissolved oxygen, and fluorides. As for heavy metals (ferrous, copper, zinc, manganese), no evidence of self-purification of surface waters has been confirmed; scientists assume that they are mostly of background origin. Researcher T. Sadova (2022) proposed approaches to solving the problem of environmental protection during armed conflicts in the legal field. The solution lies in the need to adopt the Fifth Geneva Convention, the provisions of which should address the protection of the environment during armed conflict, should contain a description of the protected areas and should specify the provisions that would apply to the restoration and protection of the environment damaged as a result of the conflict.

The Burshtyn Reservoir is a cooling pond for the Burshtyn Thermal Power Plant and is also part of the Galician

National Nature Park with the Ramsar site status of international importance. In addition to the impact of oil products and related lubricants that have entered the aquatic environment of the Burshtyn Reservoir and cause the above-mentioned environmental risks, there is another threat: a 1,000-meter flood protection dam. The total area of territories with significant flooding risks is about 2 thousand km^2 . Ash dumps are located on the territory of potential emergency flooding, and thus the risk indicators for the environment increase dramatically. In the spring of 2024, the Burshtyn Reservoir was significantly impacted by oil pollution as a result of a ballistic missile explosion. Field studies were conducted with water sampling on the same day. The purpose of the study was to assess the contamination of the Burshtyn Reservoir as a result of rocket explosions. The scientific novelty of the results obtained is that: for the first time, comprehensive environmental studies were conducted for an artificial array of surface waters that was subjected to an unusual type of pollution during military operations; the hydrochemical composition was analysed and the behaviour of individual chemical compounds under conditions of unusual pollution was determined; an environmental assessment of the state of surface waters under unusual pollution conditions was performed.

▼ Materials and Methods

Field studies were conducted to conduct an environmental assessment of the impact of oil products on the state of the Burshtyn cooling pond. The distribution of petroleum products and natural hydrocarbons vertically and along the water body's surface is quite complex. The most polluted areas are the coastal zones, where oil slicks were observed over large areas, so sampling was carried out in the surface layer of the reservoir along the perimeter of the water body. Five water samples were collected at representative sites where the content of oil products was visually observed DSTU ISO 5667-4:2003 (2004). We also collected 5 water samples for physical and chemical studies at these sites. The water quality was monitored at the sites: No. 1 – the confluence of the Hnyla Lypa River into the cooling pond; No. 2 – 400 m from the river mouth (left bank of the pond); No. 3 – 2.75 km from the river mouth (left bank of the pond, rural area); No. 4 – 2 km from the river mouth (right bank of the pond, private development area); No. 5 – the dam of the cooling pond (Fig. 1). According to V. Khilchevskyi *et al.* (2021), the Burshtyn Reservoir is classified as a medium, mid-sized and small (MMS) reservoir in Ukraine ($V_{\text{full}} = 50$ million m^3). The morphometric characteristics of the reservoir are as follows: length 7.5 km, average width 2.5 km, total water surface area 12.6 km^2 (1,260 hectares), average depth 3.5 m (maximum 8 m). The average long-term runoff of water from the reservoir for 1 year is $82 \times 10^6 \text{ m}^3/\text{year}$. Measurement of the content of petroleum products and the acidity of the medium (pH) was carried out on 12.04.2024 in Ivano-Frankivsk, Ivano-Frankivsk Region, Ukraine, in the laboratory control department of the Municipal Enterprise "Ivano-Frankivskvodoekoteprom" (Protocol No. 13/24-C of measurements of

water composition and properties). The department is certified for the right to perform measurements (Certificate of Technical Competence No. IF-402 dated 13.06.2022 issued by the State Enterprise “Ivano-Frankivsk Center for Standardisation, Metrology and Certification”). Measurements were carried out in accordance with the measurement

procedures approved for use (appendix to the certificate of attestation). The content of oil products was measured by a fluorate-02-3M fluid analyser No. 5922, and the acidity of the medium was determined using a pH/Cond3320 conductometer. Measuring instruments are approved for use by the relevant verification certificates.

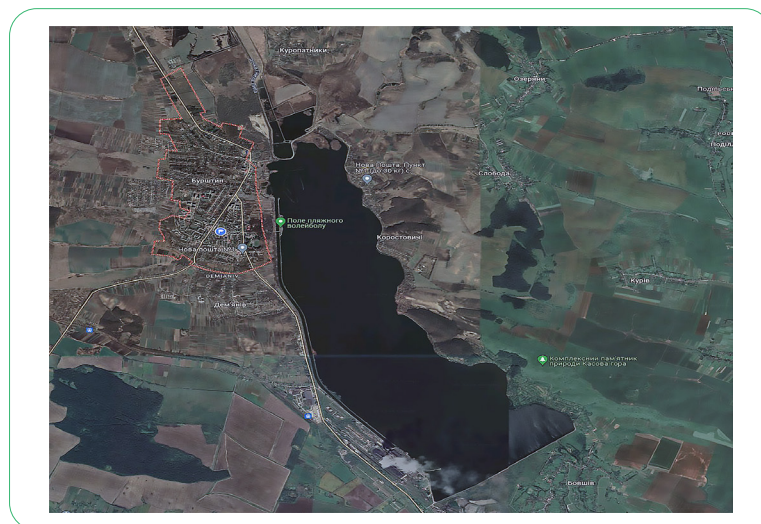


Figure 1. Representative water sampling sites in the Burshtyn cooling pond for physicochemical studies and determination of oil content (April, 2014)

Source: developed by the authors

Measurements of the content of heavy metals (HM) (cadmium, manganese, zinc, copper, chromium, and iron), nitrates, nitrites, chlorides, alkalinity, and hardness were carried out on 14.04.2024 in Kharkiv, Kharkiv Region, Ukraine, at the Educational and Research Laboratory of Analytical Environmental Studies of V.N. Karazin Kharkiv National University (Protocol No. 2006-2010 for the study of surface water). The HM content was determined by modulation polarisation spectrophotometry using an MTA 915 MD spectrophotometer, manufacturer with a hollow lamp

for the corresponding metals. The chloride content, hardness, and alkalinity were determined by titration. The nitrite content was determined using a KFK-2 photocolormeter, and the nitrate content was determined using a portable nitrometer. All measuring instruments used are authorised for use by verification certificates. The criteria for analysing the obtained results of the content of petroleum products, the chemical compounds and HM were Hygienic Water Quality Standards of Water Bodies to Meet the Drinking, Household and Other Needs of the Population (2022) (Table 1).

Table 1. Hygienic water quality standards for water bodies to meet drinking, household and other needs of the population

Name of the substance	MPC or SDT	Limiting sign of harmfulness	MPC or SDT in mg/dm ³	Hazard class
Nitrites, mg/dm ³ (for NO ₂)	MPC	s.-t.	3.3	2
Nitrates, mg/d ³ , (for NO ₃)	MPC	s.-t.	45.0	3
Chlorides, mg/dm ³	MPC	org. flavour	350.0	4
Iron, mg/dm ³	MPC	org. colour	0.3	3
Zinc, mg/dm ³	MPC	gen.	1.0	3
Copper, mg/dm ³	MPC	org. flavour	1.0	3
Manganese, mg/dm ³	MPC	org. colour	0.1	3
Cadmium, mg/dm ³	MPC	-	0.001	2
Chromium, mg/dm ³ (Cr ⁶⁺)	MPC	s.-t.	0.05	3
Heavy oil (mg/dm ³)	MPC	org. film	0.3	4

Note: s.-t. – sanitary and toxicological, affects human health; org. flavour – organoleptic, gives water an off-flavour; org. colour – organoleptic, affects the colour of water; g. – general sanitary, affects the processes of self-purification of water; org. film – organoleptic, forms a film on the surface of water

Source: made by the authors based on Hygienic Water Quality Standards of Water Bodies to Meet the Drinking, Household and Other Needs of the Population (2022)

The criteria for the analysis of ammonia content and organoleptic water quality indicators (odour, transparency

and turbidity), alkalinity and hardness were applied DSan-PiN 2.2.4-171-10 (2010) (Table 2).

Table 2. Sanitary and chemical indicators of water safety and quality

Name of the indicator (substance)	Drinking water standards in accordance with the State Sanitary and Epidemiological Norms 2.2.4-171-10
Ammonia	0.5 mg/l
Smell	≤ 2 points
Transparency	not less than 20 cm
Turbidity: quantitatively	≤ 1.0 mg/l
total alkalinity	≤ 6.5, mmol/dm ³
overall stiffness	≤ 7.0, mmol/dm ³

Source: made by authors based on DSanPiN 2.2.4-171-10 (2010)

To determine the dilution factor of pollutants in the cooling pond, the Ruffel method was used in the case of their entry into the upper third of the pond and spreading along the shore under the influence of wind disturbance. Calculations were made using the formula:

$$n_n = \frac{q+0.0087H^2}{q+0.000435H^2}, \quad (1)$$

where n_n – initial dilution when pollutants are released far from shore; q – waste water (pollutants) consumption; H – the average depth of the object where pollutants are diluted, in m. The main dilution depends on the place where the wastewater is released. For a release located far from the shore, the basic dilution is calculated using the formula:

$$n_o = 1.85 + 2.32(L/\Delta x)^{0.41 + 0.0064(L/\Delta x)}, \quad (2)$$

where n_o basic dilution; L – distance from the release of polluting water to the design alignment; $\Delta x = 4.41H^{1.167}$. The Methodology for Calculating Compensation for damage Caused to the state as a Result of Violation of Legislation on Protection and Rational use of Water Resources (2009) was used to calculate the damage caused as a result of oil products entering the water body. The calculations were based on the results of studies of the content of oil products and other pollutants in the Burshtyn Reservoir after the missile attack, and the inflation index for 2023. Ministry of Finance (2023), indexed specific economic damage from water pollution (γ) in 2023. Calculations were made using the formula:

$$Z = K_c \times K_{\text{кат}} \times K_p \times k_z \times [(M_{il} \times Y_{il}) + (M_{i2} \times Y_{i2}) + \dots (M_{iu} \times Y_{iu})], \quad (3)$$

where the coefficients take into account K_c – damage to the aquatic ecosystem; $K_{\text{кат}}$ – water body category; K_p – shortage of surface water resources; k_z – damage to the aquatic ecosystem. And the following indicators were also taken into account: μ – the amount of pollutants; M_i – mass of excess discharge of the pollutant; Y_i – specific economic damage from water pollution, determined by the formula:

$$Y_i = Y \times A_p, \quad (4)$$

where the following economic losses were accounted for: Y – indexed loss calculated based on the current year's indicators using the formula (5):

$$Y = Y_{\eta} \times I \div 100, \quad (5)$$

where Y – indexed loss calculated based on the indicators of the previous year; I – inflation index; A – relative hazard indicator that was determined by the given formula (6):

$$A_i = 1 \div MPC_i, \quad (6)$$

where MPC_i is the MPC_i of the pollutant under study. The weight of petroleum products is calculated using the following formula (7):

$$M_{\eta} = M_{\pi} - M_p, \quad (7)$$

where M_{π} – the weight of the film was calculated using the given formula (8):

$$M_{\pi} = M_{\pi\mu} \times S \times 10^{-6}, \quad (8)$$

where $M_{\pi\mu}$ – specific gravity of oil per 1 m⁻²; M_p – the mass of dissolved and emulsified oil that was calculated using the formula (9):

$$M_p = h \times S \times (C_{\eta} - C_{\phi}) \times 10^{-6}, \quad (9)$$

where h – thickness of the water layer contaminated with oil, m; S – area of oil contamination of a water body, m⁻²; C_{η} – average concentration of dissolved and emulsified oil in the contaminated volume of water under the oil slick, g/m⁻³; C_{ϕ} – background concentration of dissolved and emulsified oil in the water of this water body, g/m⁻³. The amount of damage caused to the Burshtyn Reservoir as a result of oil spills was calculated according to the Methodology for Calculating Compensation for Damages Caused to the State as a Result of Violation of Legislation on Protection and Rational Use of Water Resources (2009).

Results and Discussion

The results of studies of hydrogen ion activity in the upper part of the water body showed that the highest acidity values were recorded at two study sites: near the flood control dam (pH = 7.51 ± 0.1 pH units) and at the confluence of the Hnyla Lypa River into the reservoir (pH = 7.42 ± 0.1 pH units). In general, during the study period, conditions of neutral and acid-base balance of the environment were observed (Table 3).

Table 3. Results of testing water samples from the Burshtyn cooling pond for hydrogen reaction and oil content

Water samples	Measurement results and measurement error δ , $P=0.95$		Information about measurement methods	
	Hydrogen reaction (pH), pH units	Petroleum products, mg/dm ³	Cipher	
1	7.42 ± 0.1 pH units	16.36 ± 6.5 mg/dm ³	MBB 081/12-0317-16 PH determination	
2	7.17 ± 0.1 pH units	0.61 ± 0.24 mg/dm ³	MBB 081/12-0230-05 measurement of petroleum products	
3	6.96 ± 0.1 pH units	0.84 ± 0.34 mg/dm ³		
4	7.10 ± 0.1 pH units	1.74 ± 0.6 mg/dm ³		
5	7.51 ± 0.1 pH units	0.19 ± 0.07 mg/dm ³		

Source: developed by the authors

The analysis of the selected water samples showed that the concentration values of petroleum products were in the range from 0.19 ± 0.07 mg/dm³ up to 16.36 ± 6.5 mg/dm³. The pollutant levels exceeded the environmental standards by 54.5 times (respectively, at the MPC of 0.3 mg/dm³). Significant exceedances of the environmental standard were recorded: in the waters of the first channel ≈ 3 times, the second ≈ 54 times, the third ≈ 6 times, the fourth channel ≈ 2 times, and no exceedances were observed in the waters of the fifth channel (Fig. 1-2). Field surveys and visual observations were complicated by the fact that, as a result of wind disturbances, oil spills moved across the surface of the water body and along its perimeter during the day. The coastal part of the reservoir and a significant coastal part of the water mirror area were covered with a film of oil products.

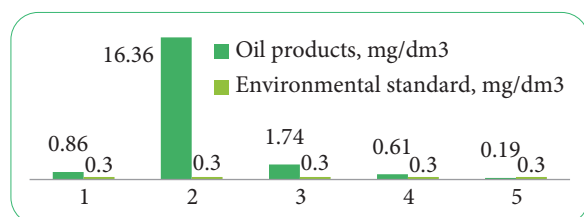


Figure 2. Comparison of oil products in the upper water layer at designated sites with their environmental standards
Source: developed by the authors

A specific feature was identified: the highest degree of acidity was characteristic of the water column with the lowest oil content. The main role in the ability of a water

body to self-purify is played by the dilution rate of water with pollutants. Water dilution is a process that reduces the concentration of pollutants in water bodies by mixing contaminated water with the surrounding water environment. The conditions for mixing polluting waters with reservoir waters differ from those in rivers. In reservoirs, the wind factor plays an important role because the currents created by the slope of the water surface are very small.

The oil products that got into the reservoir clogged a significant visible area of the water mirror. All visible oil slicks were examined for the content of oil products that had spread around the perimeter of the reservoir as a result of wind disturbance. For one of them, with the highest concentration of oil on the water surface with an area of up to 0.5 km² of oil film, and its emulsified state in the water column, the dilution coefficients for internal water exchange were calculated. Internal water exchange is characterised by the intensity of water mass transfer, turbulence, and convective processes related to the size of the reservoir. For a reservoir, the main indicators for calculating dilution are the initial (n_p) and basic (n_o) dilution (formulas 1-3). In the initial mixing zone, the concentrations of impurities are significantly reduced. However, complete mixing occurs at much greater distances from the point where pollutants enter the water body. When these substances enter a body of water at a certain distance from the shore, the initial dilution is faster. The calculated dilution ratio of contaminated water is 125.2 ($n_o = 120.4$, $n_p = 1.04$) (Rychak & Arkhypova, 2024a). In addition to petroleum products, the workstations analysed the content of heavy metals and individual physical and chemical parameters (Table 4).

Table 4. Results of physical and chemical studies of water samples of the Burshtyn cooling reservoir (April, 2024)

Name of the substance, units of measurement	Unit 1 (confluence of the Hnyla Lypa River into the reservoir)	Unit 2 private buildings, agricultural land)	Unit 3 (private buildings, agricultural land)	Unit 4 (Burshtyn, recreational area)	Unit 5 (flood protection dam)
Ammonia, mg/dm ³	0.08	0.08	0.08	0.08	0.08
Smell	0	0	0	0	0
Transparency, cm	25	25	25	25	25
Turbidity, EMF	2.0	2.0	2.0	1.5	1.5
Nitrites, mg/dm ³	0.002	0.002	0.004	0.004	0.002
Nitrates, mg/dm ³	0	0	0	0	17
Chlorides, mg/dm ³	264	264	272	256	264
Alkalinity, mmol/dm ³	3.6	4.0	5.2	5.5	4.2
Hardness, mmol/dm ³	7.0	7.6	7.8	9.0	7.8

Table 4. Continued

Name of the substance, units of measurement	Unit 1 (confluence of the Hnyla Lypa River into the reservoir)	Unit 2 (private buildings, agricultural land)	Unit 3 (private buildings, agricultural land)	Unit 4 (Burshtyn, recreational area)	Unit 5 (flood protection dam)
Iron, mg/dm ³	0.0204	0.0346	0.0289	0.00421	0.02506
Zinc, mg/dm ³	0.006	0.006	0.006	0.008	0.004
Copper, mg/dm ³	0	0.001	0	0	0
Manganese, mg/dm ³	0.004	0.002	0.004	0.001	0
Cadmium, mg/dm ³	0.001	0.001	0.001	0.001	0.001
Chromium, mg/dm ³	0	0.001	0	0.001	0

Source: developed by the authors

A summarising analysis of surface water hardness and alkalinity showed that the water was within the permissible limits of environmental standards. In the water area used for recreational activities, the quantitative indicators of alkalinity and hardness differed slightly. Increased hardness (9.0 mmol/dm³) and alkalinity (5.5 mmol/dm³). The lowest indicators characterised the water at the confluence of the Hnyla Lypa River into the Burshtyn Reservoir: hardness was 7.0 mmol/dm³, alkalinity 3.6 mmol/dm³. This is due to the introduction of natural river water into the reservoir, which is characterised by lower hardness and lower alkalinity.

The content of heavy metals in the upper layer of water was investigated: ferrous, zinc, copper, manganese, cadmium, and chromium. The content of chromium and copper was not recorded in 60% to 80% of water samples. At well No. 2 (400 meters from the confluence of the Hnyla Lypa River, left bank, impacts from private development and agricultural land cultivation), the copper content was 0.0001 mg/dm³, which is one hundredth of a percent of the environmental standard (1.0 mg/dm³). In the waters sampled at the first site (the water area was under the influence of coastal recreational load), the chromium content was found to be 0.001 mg/dm³, which is 0.2% of the environmental standard (0.5 mg/dm³).

The content of manganese and zinc was detected in the waters at all study sites. However, their content, like the previous metals, was quite low. The manganese content was about 1% of the standard content (0.13 mg/dm³). The highest zinc content was recorded in the water area of recreational impact of the reservoir and amounted to about 1% of the environmental standard (1 mg/dm³). The presence of cadmium and iron was recorded in water samples at all study sites (Fig. 3).

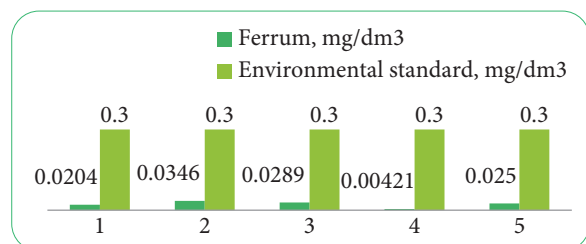


Figure 3. Ferrum content compared to the environmental standard in the surface water of the cooling pond

Source: developed by the authors

The highest content of iron was recorded in the well, where the largest oil slick was located and the highest concentration of oil products was recorded. In all other reservoirs, the content of iron was low compared to the environmental standard (about 8% of the environmental standard). The cadmium content in surface waters at the four study sites was 0.001 mg/dm³ (Fig. 4). This concentration of the pollutant is 77% of its environmental standard. This is the highest value obtained when studying the content of heavy metals in surface waters after hydrocarbons enter the reservoir.

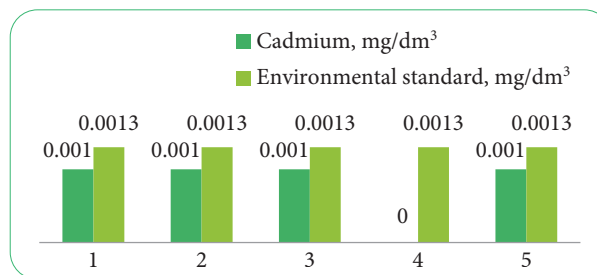


Figure 4. Cadmium content compared to the environmental standard in surface waters of the cooling pond

Source: developed by the authors

As a result of calculations, in the most polluted water area of the reservoir (the concentration of petroleum products was 16.36 mg/dm³) on an area of 0.5 km² (according to formulas 4-9) the amount of losses was 27,267.87 UAH. During the field surveys, four more, smaller in terms of concentration and area, were found to be contaminated with oil products. The amount of damage to four other areas of pollution was about 68 thousand UAH. In total, one missile attack and hydrocarbon contamination in the cooling pond caused economic losses of about 95 thousand UAH.

Burshtyn Reservoir is part of the Galician National Nature Park. In 2019, the reservoir received the conservation status of a Ramsar site of international importance. The reservoir is home to up to a hundred different species of birds, 19 of which are listed in the Red Book of Ukraine. During the spring migration, taking into account the thermal peculiarity of the drainage canal and the cooling pond, up to 22.3 thousand individuals can be in the coastal zone. Methodology for Calculating Compensation for damage Caused to the state as a Result of Violation of Legislation

on Protection and Rational Use of Water Resources (2009) when recognising the special environmental value of an ecosystem that has suffered damage as a result of pollution, the losses received increase by 1.5 times. Summarising the calculations, the total damage from hydrocarbon pollution was determined to be 143 thousand UAH.

The release of hydrocarbons into the aquatic ecosystem is an environmental disaster (Venesjarvi *et al.*, 2023), affects the state of mineralisation, specific electrical conductivity (Aluwong *et al.*, 2024), changes in water pH directly affect the survival, growth, and reproduction of fish species (Sahu *et al.*, 2024), because the suitable pH level for the growth and reproduction of fish species ranges from 6.0 to 9.0 (Mariu *et al.*, 2023). The behaviour of oil products in the aquatic environment is regulated by the processes of evaporation, sorption, spreading, biochemical and chemical oxidation, dissolution, biodegradation, dispersion, and sedimentation. Weak preparedness for natural disasters and regulatory mechanisms are also recorded, leading to serious hydrocarbon spills and their impact on the aquatic environment. In this context, in order to ensure a rapid and effective response to incidents of hydrocarbon spills in a particular area, the trajectories of their spills should be investigated, and the treatment should be carefully planned by decision support tools to eliminate emergency oil spills (Yang *et al.*, 2021).

A film on the surface of the water formed from oil residues or other lubricants and fuels prevents heat, water, and gas exchange between the water body and the atmosphere. This leads to carbon dioxide absorption, oxygen production, and the creation of primary products as a result of phytoplankton photosynthesis. The organic fraction in the pond rots when there is no oxygen, and this leads to a pestilence of fish. If the rotting organic fraction is not collected, a bacteriological threat arises. The oxidation of oil products in their natural state is very slow and requires a lot of oxygen, and they also pollute the entire water column at all horizons – on the surface as a film, in the thickness as a solution, and at the bottom as a heavy sediment. As for the surface contamination in the form of a film, studies conducted at the Burshtyn Reservoir, where the concentration of oil products exceeding environmental standards by 54 times was recorded, confirm the negative effects of hostilities that caused the destruction of the Kakhovka HPP dam in 2023 and the draining of the reservoir, discharges of pollutants with a concentration of 1.1–51.8 MPC and pollution of the estuary with an area of 6,800 km² of the system and the Black Sea, according to V. Pichura *et al.* (2024).

According to the research of V. Khilchevskyi *et al.* (2023), the content of petroleum products in the waters of the Dniester River is insignificant with a tendency to decrease average concentrations from spring flood to summer-autumn low water and to a minimum in winter low water. In the Hnyla Lypa River, where the Burshtyn Reservoir was created, and in other left-bank tributaries of the Dniester, the concentration of oil products during spring floods is 0.007 mg/dm³ (with a range of 0.004 to 0.015 mg/dm³ in different rivers), and in summer low

water 0.005 mg/dm³ (with a range of 0.002 mg/dm³ to 0.007 mg/dm³). In all the rivers and left-bank tributaries of the Dniester that were studied, the absence of oil products in the water was recorded in different years. Zero values of petroleum products were recorded in 75–80% of the water samples analysed.

As a result of research by S. Hughes *et al.* (2023) found that seasonality factors and morphological characteristics (shallow water, estuaries, bays) of the water body where the oil spill occurred are extremely important. The strength and direction of the wind has a significant impact on the spread of oil products on the water surface. During the visual assessment of the movement of oil products in the Burshtyn Reservoir, it was noted that shallow water and small bays (rugged coastline) significantly contribute to the presence and stagnation of oil products, the formation of oil slicks and their persistence in shallow water and inshore bays for a certain period of time. Regulatory processes for oil spills have a different impact on the scale of the disaster. The concentration of petroleum products and their derivatives in surface waters can significantly decrease and their chemical composition can change. An important indicator is the location of the pollutant source, mixing of water masses, and the quality of the natural water state. Changes in the types and nature of pollutants entering the reservoir change over time, which may be the reason for the increase in water pH observed in this study (from 6.5 pH to 7.5 pH), confirming the results of studies conducted in the Hirakud reservoir (Hussain *et al.*, 2020). Water environment factors, such as hardness, pH, salinity and alkalinity, affect the toxicity of heavy metals, zinc toxicity to aquatic organisms decreases with increasing water hardness (Li *et al.*, 2021), so the study of physicochemical properties of water, concentration of heavy metals is important for further research on water toxicity and its hydrochemical characteristics (Rychak & Arkhypova, 2024b). Prior to the hydrocarbon pollution, in the fall of 2023, a slightly polluted water quality class was observed at the accident site, where the concentration of oil products exceeded the MPC by up to 2 times, and where the water quality class was clean water, the concentration of oil products exceeded the MPC by 6 to 54 times.

The vulnerability of aquatic and terrestrial ecosystems to hydrocarbon pollution was calculated in monetary, quantitative, spatial, and high-resolution detail by assessing physical, biological, and socioeconomic indicators (Feng *et al.*, 2021). To ensure a fast and effective response to oil spill incidents in a particular area, the trajectory of the oil spill needs to be predicted and the clean-up needs to be carefully planned in advance. According to J. Neafie *et al.* (2024), scientists focus exclusively on physical sensitivity when studying the vulnerability of the coast and aquatic ecosystem to oil spills, thus neglecting socioeconomic factors. One explanation is that assessing the socio-economic impact of oil pollution is difficult due to the lack of proper reporting and monitoring. The proposed methods for calculating damages take into account the hazardousness of the pollutant, its concentration on the surface of the water body, in the water

column, location relative to the coastline, and the depth of the water body at the point of pollutant ingress. However, the methodology does not take into account socio-economic indicators, which are precisely the basis for the provision of ecosystem services (fisheries, tourism, cultural heritage). Studies by R. Venesjarvi *et al.* (2023) have shown that accidental oil pollution poses an additional threat to water systems, primarily in terms of oil-related losses and recovery potential. Aquatic and coastal ecosystems are regions of high biological productivity and accessibility, they have become centres of human activity, and provide important ecosystem services such as recreation, fisheries, and nutrient cycling. These ecosystems should be protected based on their conservation value, restoration potential and protection effectiveness. Vulnerability of aquatic and coastal ecosystems to oil spills is a measure of the level of sensitivity, impact and resilience of these areas in terms of biological, geological and socio-economic resources affected. Therefore, the determination of economic losses made it possible to estimate the losses caused by oil products.

✓ Conclusions

Military aggression has a very negative impact on the state of the water body. As a result of a single missile strike, rocket debris and fuel entered the Burshtyn Reservoir, which is part of the power plant's technological cycle and has the environmental status of a Ramsar site of international importance. It was found that a single missile strike led to the release of hydrocarbons into the reservoir, which exceeded the environmental standard by 54.5 times; the surface spread of oil products depends on the strength and direction of the wind and the ruggedness of the coastline. The combination of these factors indicates the maximum accumulation and increase in the concentration of hydrocarbon pollution. It was found that the water was within the permissible limits of environmental standards in terms of hardness and alkalinity. But with a water hardness of

7.6-7.8 mmol/dm³ there is a significant concentration of petroleum products, exceeding the maximum permissible concentration by 54 times, with a hardness of 9.0 mmol/dm³, the excess of petroleum products was up to 2 MPC.

It has been determined that among the six heavy metals contained in military missile fuels and lubricants, after hydrocarbon contamination, a significant cadmium content and a slightly lower iron content were found in the upper layers of surface waters. Other metals (zinc, manganese, copper, chromium) were at their lowest levels. The study determined that the dilution factor of contaminated water is 125.2. The amount of damages caused by violation of the legislation on the protection and rational use of water resources was calculated. In total, one missile attack caused economic losses of about 143 thousand UAH. It is necessary to continue researching water toxicity, conducting further studies of the state of the reservoir bottom sediments and microbiological studies, and research on the state of aquatic life to assess the full extent of missile aggression on artificial surface water bodies and to develop effective measures to minimise the negative effects. When calculating economic damages, take into account socio-economic factors that are the basis of ecosystem services not only for the aquatic ecosystem but also for the coastal ecosystem.

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✓ Conflict of Interest

None.

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Екологічна оцінка впливу вуглеводневого забруднення на стан водойм-охолоджувачів

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✔ **Анотація.** Вуглеводневе забруднення залишається важливою та невирішеною проблемою, що загострилася під час повномасштабного вторгнення, зокрема через потрапляння уламків ракет зі значною кількістю нафтопродуктів у поверхневі води. Метою роботи було надати оцінку екологічного стану водного об'єкту, що зазнав вуглеводневого та інших нехарактерних забруднень. Польові методи: було відібрано 5 проб вод для визначення вмісту нафтопродуктів та величини рН та 5 проб вод для визначення фізичних властивостей, головних іонів та вмісту важких металів. Лабораторно-інструментальні: титриметричний – застосовано для визначення вмісту хлоридів, лужності, твердості. За результатами досліджень встановлено, що хлоридні іони знаходились у межах 264-274 мг/дм³, показники лужності – 3,6-5,5 ммоль/дм³. У результаті дослідження твердості встановлено, що води м'які. Фотоколориметричним методом визначався вміст нітритів (зафіксовано їх сліди). Вимірювання: електрометричним методом визначено величину рН. За результатами вода відноситься до нейтральних та слаболужних вод. Методом флуориметрії визначено вміст нафтопродуктів у межах 0,19-16,36 мг/дм³ (перевищення еконормативу в 54,5 рази). Методом модуляційної поляризаційної спектрофотометрії визначено вміст кадмію, цинку, мангану, купруму, хрому, феруму. Вміст хрому, кадмію, купруму знаходився у межах 0,001 мг/дм³, вміст мангану – від 0,001 мг/дм³ до 0,004 мг/дм³, вміст цинку – від 0,004 мг/дм³ до 0,008 мг/дм³, вміст феруму – від 0,004 мг/дм³ до 0,02 мг/дм³. За допомогою методу Руффеля визначено загальну кратність розведення стічної води на водосховищі, що становить 125,24. За методикою розрахунку розмірів відшкодування збитків був визначений збиток від вуглеводневого забруднення, який становить 143 тис. грн. Практична цінність роботи полягає у вдосконаленні наукових та практичних підходів щодо визначення стратегії проведення комплексного екологічного дослідження стану багатофункціональних штучних водних об'єктів

✔ **Ключові слова:** нафтопродукти; водосховище; екологічні нормативи; екологічний стан; кратність розведення води; економічні збитки



Radioactivity of ^{137}Cs and ^{90}Sr components of the environment in the post-Chernobyl period in 2024

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✓ **Abstract.** The aim of the study was to determine the specific activity of environmental components and forestry products in the Bilokorovychi Village, Korosten District, Zhytomyr Region, for the content of radionuclides ^{137}Cs and ^{90}Sr , which entered them as a result of the accident at the Chernobyl Nuclear Power Plant. The study was conducted in accordance with the research topic “Monitoring studies of the biosphere of the Ukrainian Polissya” from September to November 2024 using dosimetric and radiometric methods. It was established that the exposure dose rate of gamma radiation complies with the radiation safety standards of Ukraine for populated areas: 18.3 ± 1.6 $\mu\text{R/h}$ was recorded in the forest, 12.7 ± 0.7 $\mu\text{R/h}$ on agricultural land, and 14.7 ± 3.4 $\mu\text{R/h}$ in the residential part of the village. The stems, leaves and dry fruits of blueberries exceed the requirements of DR-2006 for ^{137}Cs content by 1.7 times and by 300 Bq/kg, respectively, while the activity of ^{90}Sr is within the normal range. The specific activity of chaga, Viburnum and rosehip fruits complies with the requirements of DR-2006 and is 48.5 ± 3.6 Bq/kg, 13.7 ± 1.2 Bq/kg for ^{137}Cs content, 27.9 ± 1.7 Bq/kg, and ^{90}Sr activity is 89.9 ± 6.7 Bq/kg, 0.1 ± 0.01 Bq/kg, 0.1 ± 0.02 Bq/kg, respectively. The samples of honey mushrooms are suitable for consumption, since the specific activity of ^{137}Cs is three times lower than the standard, and that of ^{90}Sr is four times lower. The specific activity of porcini mushrooms for ^{137}Cs is 2.1 times higher than the standard, and the accumulation of ^{90}Sr is 15.7 times lower than the standard. The specific activity of moss for ^{137}Cs is almost 5 times lower than the specific

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activity of soil, which was 893.9 ± 91.3 Bq/kg for ^{137}Cs . Water from artesian wells in the village is suitable for consumption in terms of radiation indicators. Acorns moderately accumulate ^{137}Cs and ^{90}Sr (372.1 ± 17.2 Bq/kg and 143.9 ± 10.4 Bq/kg, respectively). Thus, studies have established that dry blueberries and dried porcini mushrooms are unfit for consumption

✔ **Keywords:** specific activity; permissible levels of radionuclide content; nuclear power plant accident; gamma radiation exposure dose rate; radiation safety; environmental components

✔ Introduction

All citizens residing in Ukraine must be protected from ionising radiation. Law of Ukraine No. 15/98-BP (1998) regulates the exposure of the population without taking into account the dose received from local natural background radiation. Changes in the natural radiation background occurred in 1986 after the accident at the fourth power unit of the Chernobyl Nuclear Power Plant (ChNPP). The Chernobyl disaster led to radioactive contamination of a significant part of Ukraine. Depending on the presence of long-lived radionuclides and their activity in a particular area, the territory was zoned as follows: exclusion zone, zone of unconditional (mandatory) resettlement, zone of guaranteed voluntary resettlement, zone of enhanced radioecological control (Law of Ukraine No. 791a-XII-BVR, 1991). According to Law of Ukraine No. 2697-VIII (2019), radioecological monitoring is an important component of ensuring not only environmental but also national security.

The content (activity) of radionuclides was determined in environmental components in accordance with Resolution of the Cabinet of Ministers of Ukraine No. 391-98-p (1998): atmospheric air and precipitation, water bodies (surface, marine, underground, in nature conservation areas), soil. Research on the presence of radionuclides was also conducted in industrial emissions into the atmosphere, wastewater, landfills, and radioactive waste disposal sites. The background amount of radionuclides is determined in terrestrial and marine ecosystems and landscapes. The Ministry of Environmental Protection and Natural Resources organises the study of the radiation situation at stationary points. As noted by scientists G. Cannon & J.G. Kiang (2020), the search for radiation biomarkers in ecosystems continues 34 years after the global accident. Scientists G.M. Chobotko *et al.* (2024) have developed measures to reduce the radiation dose to the population and the content of radioactive substances in soil, water, and food, and have analysed data from 38 years after the Chernobyl accident. Researchers L.M. Oleshchenko & M.O. Ilyin (2023) and E. Nagorny (2024) concluded in their works that it is important not only to determine the current state of radionuclide contamination, but also to establish migration mechanisms and distribution patterns, all of which should be used to predict the state of the environment. As noted by researchers O. Dunaievska *et al.* (2024), in connection with the armed aggression of the Russian Federation, changes have occurred in the environment, especially in areas of combat operations, where military, sabotage and terrorist actions can lead to additional release of radionuclides into the environment, posing a threat to

the population. Loss of control over the source of ionising radiation and ignorance of the algorithm of actions in such situations lead to a negative impact on the environment and exposure of people to radiation. To prevent this, according to scientists O. Sitnikova & A. Melnyk (2022), it is necessary to constantly study the issue of the vulnerability of sources of ionising radiation. However, as discussed in the work of K.O. Krushelnytska (2022), effective physical protection must be developed for employees who perform their duties in areas with increased radiation levels, such as law enforcement officers. As noted by V.P. Kovalskiy *et al.* (2021), such physical protection can be provided by the rational use of building materials.

In order to ensure rapid response and information gathering, a Strategy for an Integrated Automated Radiation Monitoring System was developed in April 2022, which will enable timely measures to be taken to protect people and the environment (Order of the Cabinet of Ministers of Ukraine No. 323-p, 2022). Such a system will make it possible to inform the international community about the radiation status of Ukraine's territory and to receive similar data from partners. After all, a radiation accident also occurred in Japan, the consequences of which are being studied by scientists who are providing recommendations on how to manage the situation (Drebot & Zamula, 2020). Therefore, as summarised by G.S. Kalda *et al.* (2022), studying the state of radiation contamination of territories is relevant not only for Ukraine but also for all countries of the world and is carried out in accordance with national monitoring programmes. The radiation safety of humanity is considered a global problem. After all, sources of ionising radiation are used not only in atomic energy and nuclear weapons, but also in medicine, agriculture, various industries, and scientific research. The number of such technologies is increasing, their scope of use is expanding, and therefore, according to Y. Kozubenko (2022), there is a need to assess the cumulative effect of ionising radiation sources.

V. Tiutiunyk *et al.* (2020) concluded in their work that it is important to develop a dynamic model of radioactive contamination of any component of the ecosystem, and that a comprehensive approach will allow conclusions to be drawn about the amount of radiation exposure of the population. It is also important to establish the distribution and content of radionuclides in the environment 38 years after the Chernobyl accident. Therefore, the aim of the study was to determine the specific activity of ^{137}Cs and ^{90}Sr in soil, water, forestry products and the exposure dose of gamma radiation in the air in the Bilokorovychi Village, Korosten

district, Zhytomyr region, since the villagers constantly harvest, consume and use berries and mushrooms that grow in the forest and undergrowth. The scientific novelty lies in obtaining reliable and comprehensive information about the state of radiation safety, radionuclide contamination of the area and plant products of a particular settlement, since the population, despite warnings, consumes such products, which are available and can be harvested within place of residence.

✓ Materials and Methods

The research was conducted in accordance with the research topic “Monitoring Studies of the Biosphere of the Ukrainian Polissya”, approved by the Ministry of Education and Science of Ukraine (state registration number 0124U000645) in September–November 2024. Radiological studies and sampling were carried out in the Bilokorovychi Village, Korosten District, Zhytomyr Region. According to Law of Ukraine No. 791a-XII-BVR (1991), the village is classified as a zone of guaranteed voluntary resettlement. Soil sampling was carried out in accordance with DSTU 4287:2004 (2004). Spot samples were obtained using a BP-25-15 drill at a depth of 0–25 cm. Sampling was carried out at a distance of more than 50 m from roads. Spot samples were formed into a nest sample weighing at least 1 kg. Visibly noticeable foreign impurities, such as fauna elements and vegetation residues, were removed from the sample. The selected samples were placed in bags, labelled, transported to the laboratory, and dried at room temperature in a well-ventilated dry room for 24 hours. Water samples were taken in accordance with DSTU ISO 5667-11:2005 (2005) from wells with a volume of at least 2 litres each.

Food samples (porcini mushrooms, honey mushrooms, blueberries, *Viburnum*, rosehips) were collected in accordance with State Hygienic Standards “Permissible Levels of Cs¹³⁷ and Sr⁹⁰ Radionuclides in Food and Drinking Water” (2006). To determine the activity of radionuclides in products, spot samples were first selected and combined into a composite sample, from which a portion was taken to form a mean sample. It was the mean sample from the crushed raw material that was used for radiological studies, from which a counting sample was weighed. Using a similar method, spot samples were taken and a counting sample was formed from moss, acorns, and chaga.

All radiological determinations were carried out in the Measurement Laboratory of the Polissya National University, which underwent an audit of the measurement system in 2022. The specific activity of the samples was determined using an MKS-AT1315 gamma-beta spectrometer (manufactured by ATOMTEKH, Republic of Belarus). The values were obtained in two stages: measurement of the working background spectrum and measurement of the activity of the sample weights. The working background spectrum was measured for 3 hours in advance and recorded in the memory of the MKS-AT1315 gamma-beta spectrometer. The control background spectrum was also measured and recorded in advance in a similar manner. The activity

of radionuclides was measured by placing sample weights in a Marinelli vessel, which was transferred to the protection unit of the MKS-AT1315 gamma-beta spectrometer using the instructions and SPTR software.

The activity was measured on the MKS-AT1315 gamma-beta spectrometer by registering gamma and beta radiation with scintillation detection units. A detection unit with sodium iodide crystals 63 mm in diameter and 63 mm in height was used to register gamma radiation. A detection unit with polystyrene activated with para-terphenyl 128 mm in diameter and 9 mm in height was used to register beta radiation. The result of the registration was instrumental spectra, which were displayed in real time on a personal computer monitor. The exposure dose rate of gamma radiation was determined using a device from the measurement laboratory, a MKG-AT1321 spectrometer-dosimeter (manufactured by ATOMTEKH, Republic of Belarus). The device continuously counted gamma radiation pulses using a scintillation detector (sodium iodide crystals with a diameter of 25 mm and a height of 40 mm) and a built-in Geiger-Müller gas discharge counter. Statistical processing of the measurement results was performed by calculating the mean value and deviation from the mean value. All studies of cultivated and wild plants, including sample collection, were conducted in accordance with applicable institutional, national or international standards and met the requirements of the Convention on Biological Diversity (1992).

✓ Results and Discussion

Radiological studies have established that the exposure dose of gamma radiation in the Bilokorovychi Village does not exceed 20 µR/hour (Table 1).

Table 1. Radiation safety indicators for atmospheric air in the Bilokorovychi Village

Measurement location	Gamma radiation exposure dose rate, µR/h
Forestry area	18.3 ± 1.6
Agricultural land	12.7 ± 0.7
Village area	14.7 ± 3.4

Source: provided by the authors

This indicator fully complies with Ukrainian radiation safety standards (State Hygienic Standards..., 1997). Determining the specific activity of soil is important in the soil-plant-animal-human chain. The activity of plant and animal products depends on the activity of the soil. Particular attention should be paid to radiological studies in areas of radioactive contamination. Studies by L. Romanchuk *et al.* (2019a) examined the specific activity of soil from such areas and determined high concentrations of radionuclides. Studies of agricultural land in the Bilokorovychi Village also indicate high specific activity in ¹³⁷Cs samples (Table 2). Long-term studies allow for the accumulation and analysis of material and the prediction of the distribution and accumulation of radionuclides, in

particular ^{137}Cs . The more time has passed since the Chernobyl accident, the better the dynamics of its distribution have been studied. Landscapes are neutral in this respect, with positive and negative balances. ^{137}Cs accumulates more on slopes and at the edge of swamps, as well as in the layers of macromycetes, lichens and mosses. The soil retains

almost 87% of the radionuclide ^{137}Cs (Orlov, 2021). The concentration of ^{137}Cs is an important indicator for studying the suitability of products for the population not only in the case of environmental contamination after the Chernobyl accident, but also after the Fukushima accident, since the half-life is 30 years, as noted by M. Hachinohe *et al.* (2021).

Table 2. Radiation safety indicators of samples of environmental components and food from Bilokorovychi village

Sample name	Specific activity for ^{137}Cs , Bq/kg	Permissible level for ^{137}Cs , Bq/kg	Specific activity for ^{90}Sr , Bq/kg	Permissible level for ^{90}Sr , Bq/kg
Soil	893.9 ± 91.3		0.1 ± 0.05	
Water	1.5 ± 0.09	2	0.1 ± 0.01	2
Moss	165.8 ± 10.3		0.1 ± 0.03	
Chaga	48.5 ± 3.6	200	89.9 ± 6.7	100
Acorns	372.1 ± 17.2		143.9 ± 10.4	
<i>Viburnum</i> (fruit)	13.7 ± 1.2	70	0.1 ± 0.01	10
Blueberry (stem with leaves)	347.5 ± 5.8	200	0.1 ± 0.02	100
Blueberry (fruit, dried)	$2,798.4 \pm 21.3$	2,500	96.7 ± 9.3	250
Rosehip (fruit)	27.9 ± 1.7	70	0.1 ± 0.02	10
Honey mushrooms	146.8 ± 10.6	500	3.7 ± 0.2	50
Porcini mushrooms (dried)	$5,292.4 \pm 22.7$	2,500	15.9 ± 0.7	250

Source: provided by the authors

Ionising radiation affects human health and life. The dose of internal exposure is formed by the consumption of food and drinking water containing radionuclides. Food can account for up to 95% of the internal exposure dose if such products are grown, consumed and consumed in a radioactively contaminated area. Chronic exposure is particularly common among residents of radioactively contaminated areas. Polissya ecosystems, in particular oligotrophic and mesotrophic bogs, were contaminated with radioactivity back in 1986. Research by scientists has established the intensive migration of the radionuclide ^{137}Cs . The specific activity of shoots and berries of the cranberry (*Vaccinium oxycoccus* L.) has significantly decreased (Krasnov *et al.*, 2022). The fruits of blueberries growing in Polissya are widespread and commonly consumed. Common blueberry (*Vaccinium myrtillus* L.) of the *Ericaceae* family is used in medicine in the form of dried fruits and leaves. It grows in the form of a small bush. Radiometry has established that the stems and leaves of blueberries exceed the established permissible levels (State Hygienic Standards..., 2006) by 1.7 times in terms of ^{137}Cs content, while the activity of ^{90}Sr is within the normal range (Table 2).

Dried blueberries do not meet the established permissible levels for ^{137}Cs activity, exceeding the limit by almost 300 Bq/kg, while ^{90}Sr activity meets the requirements of the State Hygienic Standards "Permissible Levels of Cs^{137} and Sr^{90} Radionuclides in Food and Drinking Water" (2006). The need to study porcini mushrooms (*Boletus edulis* Bull. ex Fr.; or *Boletus bulbosus* Schaeff. ex Schroet.) of the *Boletaceae* family for radionuclide content is due to the special demand for this product on the food market compared to other types of mushrooms. They were studied in dry form. The specific activity of porcini mushrooms for ^{137}Cs is 2.1 times higher than normal, although for ^{90}Sr it is 15.7 times lower than normal (Table 2).

Studies of dried blueberry samples conducted by scientists L. Romanchuk *et al.* (2019b) in the Ovruch and Narodychi districts of the Zhytomyr region, which are classified as areas of radioactive contamination, showed that permissible levels were exceeded by up to 5 times in some cases, making such products unfit for consumption. There were four settlements in the voluntary guaranteed resettlement zone where the specific activity of blueberries for ^{137}Cs was within the range of 565-665 kBq/kg. Similarly, in the Narodychi and Ovruch districts, significant radioactivity was observed in dry porcini mushrooms (2,058-12,870 kBq/kg). Scientists K. Beňová *et al.* (2021) also obtained results in their work that indicate that the activity of ^{137}Cs in the soil exceeds its content in blueberry leaves and stems. This confirmed the need for radioecological monitoring with the selection of various samples for further analysis.

The results of 10 years of observations in a large-scale analytical work by V. Kotelevych & O. Pinsky (2022) showed that exceedances of permissible levels in forest products, including mushrooms and berries, were recorded in almost 39% of samples. Exceedances of the radionuclide ^{137}Cs content in accordance with the State Hygienic Standards "Permissible Levels of Cs^{137} and Sr^{90} Radionuclides in Food and Drinking Water" (2006) were found in mushrooms and berries in the Narodychi, Olevsk, Korosten, Luhyn, and Yemilchyn districts. In particular, almost 14% of forest berry samples did not meet the requirements, especially those from the Narodychi and Ovruch districts. Mushrooms, especially porcini mushrooms, had the highest specific activity. These results only confirm the reliability of the current study. In 2017, the analysis of food samples registered the highest proportion of exceedances of permissible levels of radionuclides from the Narodychi and Ovruch districts, with mushrooms and forest berries accounting

for a significant proportion. In 2019, approximately 0.1% of the samples selected were found to be non-compliant in terms of specific radioactivity, including mushrooms and medicinal plants. In 2020, high specific activity was again found in forest berries and mushrooms.

Chaga, or birch mushroom, of the *Hymenochaetaceae* family grows as growths on birch trees and is used in medicine. In terms of specific activity, this mushroom meets the established requirements. Attention should be paid to the peculiarity of the radionuclide content: the activity of ^{90}Sr is 1.9 times higher than that of ^{137}Cs (Table 2). *Viburnum* of the *Adoxaceae* family is a shrub 150 cm high. When raw, the fruits can be stored for a long time. They are used as a food product. In terms of specific activity, *Viburnum* fruits meet the established requirements, with the activity of ^{90}Sr being 10 times and the activity of ^{137}Cs being 5 times lower than the norm prescribed in the State Hygienic Standards "Permissible Levels of Cs^{137} and Sr^{90} Radionuclides in Food and Drinking Water" (2006) (Table 2).

Rosehip (*Rosa* L., 1753) of the *Rosaceae* family is known as a shrub, the most common species being *Rosa canina* L. It is used in medicine, most often in the form of dried fruits. In terms of specific activity, rosehip fruits meet the established requirements, with ^{90}Sr activity 10 times and ^{137}Cs activity 2.5 times lower than the norm specified in the regulatory document State Hygienic Standards "Permissible Levels of Cs^{137} and Sr^{90} Radionuclides in Food and Drinking Water" (2006) (Table 2).

Honey mushrooms are lamellar cap mushrooms that mainly grow on stumps and trees. They include various species: winter, spring, summer, meadow, autumn honey mushrooms and others. It is considered a food product in its raw form, which, after testing, can be used for culinary processing. The selected samples of honey mushrooms meet the established requirements (Table 2). V. Kotelych et al. (2024) noted that, according to statistical data, in 2023, mushrooms were found in dry and fresh form with an excess of radionuclides according to the State Hygienic Standards "Permissible Levels of Cs^{137} and Sr^{90} Radionuclides in Food and Drinking Water" (2006). However, the type of mushrooms was not specified. It was assumed that this does not apply to honey mushrooms, as they grow above the forest litter level, which is what contributes to their relatively low radionuclide content.

There are many species of mosses (*Bryophyta*). The current study observed forest moss (*Sphagnum*). It attracted attention due to its prevalence and use as a decorative material in homes and as a basis for keeping some animals at home. Scientists use moss to measure the level of external radiation and air pollution, as noted by L. Barandovski et al. (2021). They proposed a model for calculating the radiation dose using the results obtained. Therefore, the study of the specific activity of moss is valuable from the point of view of radioecology. The specific activity of moss for ^{137}Cs is almost 5 times lower than the specific activity of soil (Table 2). Therefore, its use in small quantities in everyday life will not contribute significantly to the total radiation dose

to humans. It should be noted that the specific activity of soil for ^{137}Cs is almost 9,000 times higher than for ^{90}Sr . This difference can be explained by the sorption capacity of radionuclides, which is obviously lower for ^{90}Sr than for ^{137}Cs , as noted by O.V. Nikitina (2021). The research is consistent with the data obtained by scientists Y. Guan et al. (2023) in the southern region of Guangdong, China. In particular, the specific activity of soil is five times higher than that of moss.

In the context of sustainable development, afforestation and reforestation in radiation-contaminated areas are important tasks. To this end, it is necessary to take into account the properties of radionuclide retention by forest ecosystem components and to implement certain measures. Shrubs, herbaceous plants and fungi accumulate almost 90% of radionuclides. Woody plants accumulate radionuclides in different ways, for example, conifers more than deciduous trees. Among the physiological properties of plants that need to be taken into account is the annual growth of wood. In oak and hornbeam, these indicators are low, so the accumulation of radionuclides is insignificant (up to 60 Bq/kg), while pine in the same conditions will have a specific activity of 70–500 Bq/kg (Trohymchuk, 2024). Acorns are the fruits of the common oak (*Quercus robur*) of the beech family (*Fagaceae*). During the study, acorns were considered as wild berries. Despite the fact that in the State Hygienic Standards "Permissible Levels of Cs^{137} and Sr^{90} Radionuclides in Food and Drinking Water" (2006), acorns are not listed, they were studied as a product from which coffee and flour can be made, as well as used as feed for farm animals. In this case, the regulatory content for ^{137}Cs is 500 Bq/kg, and for ^{90}Sr – 50 Bq/kg. Acorns accumulate a fairly large amount of Chernobyl radionuclides: 372.1 ± 17.2 Bq/kg and 143.9 ± 10.4 Bq/kg for ^{137}Cs and ^{90}Sr , respectively (Table 2), and it is precisely the activity of ^{90}Sr that will not meet the permissible levels. It can be assumed that acorns contribute to the radioactivity of forest litter. Therefore, acorns from this area of radioactive contamination are characterised by an increased level of radionuclide accumulation and are dangerous for use in the food industry and for burning as a source of heat.

✓ Conclusions

Radiological studies have established that the exposure dose of gamma radiation in the Bilokorovychi Village, Korosten District, Zhytomyr Region, complies with Ukrainian radiation safety standards established for populated areas. The highest gamma radiation exposure dose was recorded in the forestry area (18.3 ± 1.6 $\mu\text{R/h}$), and the lowest in agricultural land (12.7 ± 0.7 $\mu\text{R/h}$). The specific activity of blueberry stems and leaves is 347.5 ± 5.8 Bq/kg for ^{137}Cs (1.7 times higher than the standard) and 0.1 ± 0.02 Bq/kg for ^{90}Sr (1,000 times lower than the standard). The specific activity of dry blueberry fruits is $2,798.4 \pm 21.3$ Bq/kg for ^{137}Cs (298.4 times higher than the norm) and 96.7 ± 9.3 Bq/kg for ^{90}Sr (153.3 times lower than the norm). That is, the stems, leaves and dry blueberries exceed the established state hygiene standards for ^{137}Cs content, while the activity of ^{90}Sr is within the norm and is unsuitable for consumption.

The specific activity of chaga, *Viburnum* berries and rosehips (dry) meets the established requirements for both ^{137}Cs and ^{90}Sr content. The samples of honey mushrooms are suitable for consumption (the specific activity for ^{137}Cs is 2.7 times lower than the norm and 13 times lower for ^{90}Sr). The specific activity of dry porcini mushrooms for ^{137}Cs ($5,292.4 \pm 22.7$ Bq/kg) is 2.1 times higher than the norm (2,500 Bq/kg), for ^{90}Sr – 7 times lower than the norm, they are unfit for consumption. The specific activity of moss for ^{137}Cs is almost 5 times lower than the specific activity of soil, which was 893.9 ± 91.3 Bq/kg for ^{137}Cs . The specific activity of acorns is 372.1 ± 17.2 Bq/kg and 143.9 ± 10.4 Bq/kg for ^{137}Cs and ^{90}Sr , respectively, which does not allow them to be recommended as a food product. Authors consider it promising to expand the scope of research, in particular, to cover trees and shrubs of different ages, forest litter, and game. In

the future, the authors intend to analyse the specific activity of oaks of different age categories and acorns from areas of enhanced radioecological control and from areas that are conditionally clean from radionuclide contamination.

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✓ Conflict of Interest

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Радіоактивність за цезієм-137 та стронцієм-90 складових довкілля післячорнобильського періоду у 2024 році

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✔ **Анотація.** Метою роботи було визначити питому активність складових довкілля та лісгосподарської продукції села Білокоровичі Коростенського району Житомирської області на вміст радіонуклідів ^{137}Cs та ^{90}Sr , що надійшли до них у результаті аварії на Чорнобильській атомній електростанції. Дослідження виконувалося згідно з темою науково-дослідної роботи «Моніторингові дослідження біосфери Українського Полісся» з вересня по листопад 2024 року з використанням дозиметричних та радіометричних методів. Встановлено, що потужність експозиційної дози гамма-випромінювання відповідає нормам радіаційної безпеки України для населених пунктів: $18,3 \pm 1,6$, $18,3 \pm 1,6$ мкР/год зафіксовано в лісовому масиві, $12,7 \pm 0,7$ мкР/год на землі сільськогосподарського призначення, $14,7 \pm 3,4$ мкР/год у житловій частині села. Стебло, листя та сухі плоди чорниці перевищують вимоги ДР-2006 за вмістом ^{137}Cs у 1,7 разів та на 300 Бк/кг відповідно, тоді як за активністю ^{90}Sr знаходиться в межах норми. Питома активність чаги, плодів калини та шипшини відповідає вимогам ДР-2006 і становить за вмістом ^{137}Cs $48,5 \pm 3,6$ Бк/кг, $13,7 \pm 1,2$ Бк/кг, $27,9 \pm 1,7$ Бк/кг, та за активністю ^{90}Sr $89,9 \pm 6,7$ Бк/кг, $0,1 \pm 0,01$ Бк/кг, $0,1 \pm 0,02$ Бк/кг відповідно. Зразки опеньок придатні до споживання, оскільки питома активність за ^{137}Cs втричі нижча за норматив, а за ^{90}Sr – учетверо. Питома активність білих грибів за ^{137}Cs в 2,1 рази перевищує норму, а накопичення ^{90}Sr відбулося в 15,7 разів менше за норму. Питома активність моху за ^{137}Cs майже в 5 разів менша за питому активність ґрунту, яка становила $893,9 \pm 91,3$ Бк/кг за ^{137}Cs . Вода з артезіанських свердловин села за радіаційними показниками придатна до споживання. Жолуді помірно накопичують ^{137}Cs і ^{90}Sr ($372,1 \pm 17,2$ Бк/кг та $143,9 \pm 10,4$ Бк/кг відповідно). Отже, дослідженнями встановлено, що непридатними до споживання є сухі плоди чорниці та сушені білі гриби

✔ **Ключові слова:** питома активність; допустимі рівні вмісту радіонуклідів; аварія на атомній електростанції; потужність експозиційної дози гамма-випромінювання; радіаційна безпека; компоненти навколишнього середовища



Integral assessment of the effectiveness of water resource management in communities for sustainable development

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✓ **Abstract.** The relevance of this study stems from the need to develop comprehensive monitoring systems for evaluating the effectiveness of water resource management that take into account environmental, social and economic dimensions. This study aimed to analyse and assess existing approaches to the development of an integrated monitoring system for evaluating the effectiveness of water resource management at the level of territorial communities, with the goal of ensuring environmental safety and sustainable development. The research was based on a systems approach and employed SWOT analysis, comparative analysis and modelling. Based on a review of the scientific literature, a multi-level system of indicators was developed, comprising nine key indicators grouped into environmental, social and economic components. The calculated integral indicator of water resource management effectiveness was 0.382, indicating a below-average level of effectiveness. The component analysis revealed a critical imbalance: the environmental component scored extremely low (0.03), due to the absence of designated water protection zones (0%) and the poor condition of water bodies (0% classified as in "good" condition). The social component demonstrated a relatively high result (0.6174), attributed to a high level of access to centralised water supply (89.8%) and wastewater services (87%). The economic component (0.518) reflected a moderate level of effectiveness; however, it was negatively affected by high water losses in the distribution networks (44%) and a low rate of water reuse (1%). Forecast modelling for the period up to 2050 indicated the potential to achieve a high level of effectiveness (0.963), provided that integrated measures are implemented across all key areas, with the

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most dynamic improvements expected between 2023 and 2030. The practical value of the study lies in the development of a scientifically grounded basis for assessing the effectiveness of water resource management at the level of territorial communities. This enables the identification of priority areas for improving the system and supports the adoption of evidence-based management decisions in the field of water governance

✔ **Keywords:** assessment; environmental safety; monitoring; territorial communities; quality indicators; basin-based approach

✔ Introduction

Effective water management is a key factor in ensuring environmental safety, promoting sustainable community development, and preserving water potential for future generations. In the context of increasing anthropogenic pressure, climate change and water scarcity, the development of integrated monitoring systems becomes particularly crucial. Such systems enable the assessment of water management performance at the community level. For Ukraine, which is striving to align its environmental policy with the requirements of the European Union and the United Nations (UN) Sustainable Development Goals (SDGs), the implementation of integrated approaches to water resource management represents an important strategic objective. Despite numerous studies in the field of water governance, the development of integral indicators for assessing management effectiveness at the level of territorial communities remains underexplored.

Integrated water management has emerged as a leading focus of ecosystem research between 2020 and 2024, driven by global challenges in securing water access, conserving resources and promoting rational use. The issue of comprehensive monitoring of aquatic ecosystems has been explored in detail by M.A.E. Forio & P.L.M. Goethals (2020), who developed an integrated methodology for the analysis of aquatic ecosystems based on a synthesis of hydromorphological characteristics, physicochemical properties, and biological parameters. The researchers highlight the importance of multi-tiered monitoring in ensuring sustainable water management and fulfilling the SDGs related to clean water and terrestrial ecosystems.

Current monitoring systems predominantly focus on isolated aspects of water use, often overlooking the complex interplay between ecological, social and economic factors. In contrast, European concepts of integrated water management emphasise the need to consider the full range of interconnections within water-ecological systems, aligning human needs with environmental requirements. Research conducted between 2020 and 2024 has placed increasing importance on the application of advanced monitoring technologies, particularly the use of the Internet of Things, wireless sensor networks, and real-time data collection systems. R. Martínez *et al.* (2020) developed an integrated water quality control system based on IoT technologies, enabling real-time data collection and processing. These innovations significantly enhance the responsiveness and quality of decision-making related to water use. Studies aimed at developing comprehensive performance indicators for water management, which integrate economic, social and environmental

dimensions, deserve particular attention. For instance, S. Bilalova *et al.* (2023) demonstrated in their research that such indicators allow not only for an assessment of the current state of water use but also for trend forecasting, the identification of critical influencing factors, and the formulation of evidence-based directions for improving local water policy.

Research dedicated to developing integrated groundwater-monitoring systems is particularly pertinent for Ukraine. A. Hienova *et al.* (2023) proposed a comprehensive approach to monitoring groundwater in the country's industrial regions that enables efficient identification of pollution sources and assessment of their impact on the environmental safety of water resources. Valuable insights into regional aspects of water-resource management were provided by H. Kireitseva *et al.* (2024), who examined the internal and external factors governing the use and conservation of water resources in the Zhytomyr Region. The study identified key determinants of water-use efficiency in the region, including institutional, economic and environmental factors. Findings indicated that obsolete water-supply technologies and insufficient coordination between different levels of governance exert the greatest influence on the condition of water resources. However, no specific mechanisms were suggested for integrating the identified factors into a comprehensive community-level monitoring system for management effectiveness. A promising avenue for further improvement is the integration of watermanagement strategies into land-use planning, as proposed by S. Kalogiannidis *et al.* (2023). This approach would facilitate more effective delineation and enforcement of water-protection zones – a critical element of the environmental dimension of the integral indicator. In Zhytomyr, the issue is particularly pressing, given the documented absence of designated water-protection zones for local water bodies.

An analysis of scientific literature indicates a growing interest in the development of integral indicators for assessing the effectiveness of water resource management, which combine environmental, social and economic dimensions. However, the formation of such indicators at the level of territorial communities – particularly in the context of decentralised governance in Ukraine – remains insufficiently explored. This study aimed to conduct a systematic analysis and comprehensive assessment of current approaches used to develop integrated monitoring systems for evaluating the effectiveness of water resource management at the territorial communities level, with a focus on ensuring environmental safety and sustainable resource use.

Materials and Methods

The methodological basis of the study was a systems approach to evaluating the performance of water management activities at the level of a territorial community. The research was conducted using data from the Zhytomyr urban territorial community, selected as a representative example of mid-sized Ukrainian communities that face typical challenges related to water resources. The study drew on a wide range of sources, including: official documents from Zhytomyr City Council (2023a; 2023b), such as the General Plan of the Zhytomyr Urban Territorial Community, the Sustainable Urban Mobility Plan of Zhytomyr, and the Integrated Urban Development Concept of Zhytomyr until 2030 (Ministry of Regional Development, Construction, Housing and Communal Services of Ukraine, 2019); statistical data from the Zhytomyrvodokanal municipal enterprise for 2020–2023 (Zhytomyr Vodokanal..., 2022); state statistical reporting forms 2-TP (water management), 1-housing stock, 11-NKREKP (State Statistics of Ukraine, n.d.); monitoring data from the Pripyat River Basin Water Resources Management (2023); and data from the State Water Cadastre of Ukraine (2023), the State Land Cadastre of Ukraine (2023), as well as the authors' research findings.

A range of scientific methods was applied to achieve the stated aim and address the objectives of the study. Systems analysis was used to explore water resource management comprehensively, incorporating environmental, social and economic dimensions. This made it possible to consider the water management system as a set of interrelated elements. SWOT analysis was employed to identify the strengths, weaknesses, opportunities and threats in the field of water resource management within the Zhytomyr urban territorial community. Based on the SMART methodology, the following key strategic goals and objectives were defined: ensuring effective and sustainable water resource management through the development of an integrated monitoring system and the adoption of modern water supply technologies; protecting and restoring aquatic ecosystems by delineating water protection zones and implementing ecological rehabilitation programmes; improving access to safe drinking water and sanitation by modernising infrastructure and expanding the centralised water supply network; enhancing climate resilience and preventing flooding through the development of stormwater management systems and early warning mechanisms; promoting sustainable and efficient water use by reducing water losses in distribution networks and introducing water reuse technologies.

This structuring ensured that each identified area met the criteria of specificity, measurability, attainability, relevance, and time-boundedness. To bring heterogeneous indicators (shares, percentages, absolute values) onto a unified measurement scale ranging from 0 to 1, data standardisation methods were applied – an essential requirement for calculating a composite indicator. Two standardisation algorithms were used in the study: one for increasing-type indicators (1) and one for decreasing-type indicators (2):

$$K_1 = (X - X_{(min)}) / (X_{(max)} - X_{(min)}); \quad (1)$$

$$K_2 = (X_{(max)} - X) / (X_{(max)} - X_{(min)}), \quad (2)$$

where X – the actual value of the indicator; $X_{(min)}$ and $X_{(max)}$ – the minimum and maximum possible values; K_1 – the standardised value for increasing-type indicators; K_2 – the standardised value for decreasing-type indicators.

A key element of the research methodology was the composite assessment method, which was used to calculate the overall water management performance indicator. This indicator is derived from the standardised values of the environmental, social, and economic components, weighted according to the following algorithm:

$$I = \alpha_1 E + \alpha_2 C + \alpha_3 K, \quad (3)$$

where I – the integral effectiveness indicator; $\alpha_1, \alpha_2, \alpha_3$ – the weighting coefficients (their sum equals 1); E – the environmental component; C – the social component; K – the economic component.

Each component value was calculated as the arithmetic mean of the standardised values of the corresponding indicators:

$$E = \frac{K_{1E} + K_{2E} + K_{3E} + K_{4E}}{4}, \quad (4)$$

$$C = \frac{K_{1C} + K_{2C} + K_{3C}}{3}, \quad (5)$$

$$K = \frac{N_{1K} + N_{2K}}{2}, \quad (6)$$

where $K_{1E}, K_{2E}, K_{3E}, K_{4E}$ – the standardised values of environmental indicators; K_{1C}, K_{2C}, K_{3C} – the standardised values of social indicators; N_{1K}, N_{2K} – the standardised values of economic indicators.

This approach enables the aggregation of heterogeneous indicators into a single assessment, the consideration of the relative importance of different management aspects, the tracking of overall trends, the comparison of management effectiveness across communities, and the justification of intervention priorities. The weighting coefficients α_1, α_2 , and α_3 were determined through expert evaluation based on a survey of professionals in the field of water management. The expert survey was conducted in February–March 2023 at Zhytomyr Polytechnic State University. Twelve experts participated in the study: five academics from universities and research institutions, five representatives of local government and state agencies in the water sector, and two specialists from regional water supply companies. The survey was conducted individually in a mixed format: eight in-person interviews and four remote questionnaires completed via Google Forms, with anonymity settings enabled. Experts were asked to assess the importance of each indicator and component using a ten-point scale. The results were normalised to ensure that the sum of the weighting coefficients equalled one. The study was conducted in accordance with ethical standards, following the principles of The Declaration of Helsinki (2013). All participants gave informed consent, were briefed on the purpose of the study and the intended use of the results, and were guaranteed

confidentiality of personal data and the right to withdraw from the study at any stage. The selection of environmental indicators aligns with the recommendations of M.A.E. Forio & P.L.M. Goethals (2020) regarding integrated monitoring of aquatic ecosystems. The economic indicators – particularly the water loss metric – correspond to the approaches outlined in the research of F.L.R. Tambo *et al.* (2022).

Based on the target indicators for 2030, 2040 and 2050, a simulation of the integral performance indicator was carried out. The targets include: achieving 100% coverage with centralised water supply and wastewater services by 2050, with interim targets of 93% by 2030 and 97% by 2040; reducing water losses in distribution networks from the current 44% to 30% by 2030, 20% by 2040, and 12% by 2050; increasing the share of reused water in industry from 1% to 25%, 45% and 65% for the respective periods; achieving 100% delineation of water protection zones by 2030; and improving the ecological status of water bodies, with 30%, 60% and 80% classified as in “good” condition by 2030, 2040 and 2050 respectively. The “good” condition of water bodies is defined as a condition that meets the criteria of the Directive of the European Parliament and of the Council No. 2000/60/EC (2000), in which water quality indicators ensure the proper functioning of aquatic ecosystems and their suitability for water use. These targets were developed in accordance with the strategic development documents of the Zhytomyr community (Ministry of Regional Development, Construction, Housing and Communal Services of Ukraine, 2019), the provisions of the Directive of the European Parliament and of the Council No. 2000/60/EC (2000), which has been incorporated into Ukrainian legislation, as well as the UN SDGs, in particular Goal 6 “Clean Water and Sanitation” and Goal 11 “Sustainable Cities and Communities”.

The research was carried out in four consecutive stages. During the first stage (September–December 2022), data on the condition of water resources and their management system within the Zhytomyr urban territorial community were collected and systematised, and strategic documents, statistical records and monitoring results were analysed.

The second stage (January–March 2023) focused on developing an indicator system for evaluating the effectiveness of water-resource management. The third stage (April–May 2023) involved calculating the integral watermanagement effectiveness indicator using the methodology developed. The final stage (June–August 2023) comprised an analysis of the results obtained and the formulation of recommendations for enhancing the community’s water-management system.

✓ Results and Discussion

Effective water-resource management in territorial communities necessitates a systems approach rooted in an objective analysis of the current situation and in the establishment of strategic directions for improvement. Assessment of water-sector performance in the Zhytomyr urban territorial community began with an examination of the links between strategic water-use objectives and the community’s principal planning documents. Alignment with the General Plan of the Zhytomyr Urban Territorial Community is crucial, as water-protection objectives must be integrated into spatial planning (Zhytomyr City Council, 2023a). The Integrated Urban Development Concept of Zhytomyr until 2030 is likewise pivotal, because the strategic goals of sustainable water management should correspond to the city’s overall vision and development priorities (Ministry of Regional Development, Construction, Housing and Communal Services of Ukraine, 2019). The Sustainable Urban Mobility Plan of Zhytomyr outlines measures to reduce the environmental impact of transport on water resources and to support the development of infrastructure along water bodies (Zhytomyr City Council, 2023b). The Development Strategy of the Zhytomyrvodokanal municipal enterprise to 2030 also plays an important role in setting objectives for infrastructure modernisation and reducing water losses. It is worth noting that all targets are aligned with the national SDG Ukraine Monitoring Report (2020). Based on an analysis of the current state of water resource management in the Zhytomyr urban territorial community, a SWOT analysis was conducted. The results are presented in Table 1.

Table 1. SWOT analysis of the water resource management system in the Zhytomyr urban territorial community

Strengths (S)	Weaknesses (W)
S1 – Availability of numerous lakes and reservoirs	W1 – Pollution of water bodies
S2 – Development of water supply and wastewater infrastructure	W2 – Littering with household waste
S3 – Introduction of modern water treatment technologies	W3 – Lack of comprehensive, integrated water resource management
S4 – Presence of recreational and ecological zones	W4 – Shortage of drinking water in certain areas and generally poor water quality
S5 – Public engagement in water resource protection	W5 – Underdeveloped water supply and wastewater infrastructure in some settlements; absence of sewerage systems
S6 – Water-related activities such as open-water competitions	W6 – Uncontrolled use of water resources and water protection zones
S7 – Availability of reservoirs suitable for renewable energy production	W7 – Non-compliance with regulations on riparian buffer zones and protected water areas
S8 – Availability of qualified personnel in the field of water resource protection	W8 – Inefficient water use in both industry and households
S9 – Gradual greening of industry	W9 – Outdated infrastructure and technologies
S10 – International cooperation	W10 – Insufficient cooperation between local authorities, businesses and the public
	W11 – Low public awareness
	W12 – Inadequate financial resources
	W13 – Loss of local biodiversity and increasing biological invasions
	W14 – Lack of alternative sources of drinking water

Table 1. Continued

Opportunities (O)	Threats (T)
O1 – Development of water-based tourism and recreation	T1 – Climate change (including floods and droughts)
O2 – Introduction of new water treatment and supply technologies	T2 – Hydromorphological changes
O3 – Infrastructure improvements: modernisation of dams and reservoirs, and flexible reservoir management	T3 – War and the impact of military activity on water resources
O4 – Promotion and support for water-saving technologies and the installation of local treatment facilities by businesses	T4 – Increasing pollution from industrial, agricultural and domestic sources
O5 – Creation of favourable conditions for attracting investment in infrastructure development	T5 – Unregulated well drilling and over-extraction of groundwater
O6 – Raising public awareness of the importance of preserving water resources	T6 – Soil erosion and clogging of watercourses
O7 – Development of a water resource monitoring system	T7 – Loss of biodiversity in aquatic ecosystems
O8 – Strengthening cooperation between authorities, businesses, NGOs and citizens	T8 – Lack of effective water resource management
O9 – Design and implementation of revitalisation and decontamination programmes for small rivers	T9 – Non-compliance with riparian buffer zones and protected water areas
O10 – Development of integrated stormwater drainage and treatment systems	T10 – Conflicts over water resources
O11 – Support for academic collaboration and scientific research	T11 – Risks to public health
	T12 – Negative impacts on economic development

Source: developed by the authors

Applying the principles of SMART planning, five core strategic directions were identified: ensuring effective and sustainable water-resource management; protecting and restoring aquatic ecosystems; providing access to safe drinking water and adequate sanitation; enhancing climate resilience and preventing local flooding; promoting the sustainable and efficient use of water resources. On the

basis of these goals, an indicator system was devised to monitor the effectiveness of water resource management in the Zhytomyr urban amalgamated territorial community. The system comprises nine key indicators with target values for 2030, 2040 and 2050, covering water protection, attainment of good ecological status, water-use management and infrastructure development (Table 2).

Table 2. Indicators for calculating the integral effectiveness indicator of water-resource management

No.	Indicator	Unit	Baseline (2023)	Target	Calculation formula
Environmental (E)					
1	Proportion of wastewater treated	%	97%	2030: 99% 2040: 99.5% 2050: 100%	$(\text{Volume of treated wastewater} / \text{Total volume of wastewater}) \times 100\%$
2	Proportion of water bodies with delineated water-protection zones	%	0%	2030: 100% 2040: 100% 2050: 100%	$(\text{Number of water bodies with delineated zones} / \text{Total number of water bodies}) \times 100\%$
3	Proportion of stormwater treated	%	10%	2030: 30% 2040: 60% 2050: 90%	$(\text{Volume of treated stormwater} / \text{Total volume of stormwater runoff}) \times 100\%$
4	Proportion of surface-water bodies with “good” ecological and chemical status	%	0%	2030: 30% 2040: 60% 2050: 80%	$(\text{Number of water bodies in “good” status} / \text{Total number of water bodies}) \times 100\%$
Social component (C)					
5	Level of access to centralised wastewater services	%	87%	2030: 92% 2040: 96% 2050: 100%	$(\text{Population connected to centralised wastewater services} / \text{Total population}) \times 100\%$
6	Proportion of the population with access to a centralised water supply	%	89.8%	2030: 93% 2040: 97% 2050: 100%	$(\text{Population with access to centralised water supply} / \text{Total population}) \times 100\%$
7	Level of implementation of the River Basin Management Plan measures within the community’s territory	%	0%	2030: 50% 2040: 75% 2050: 100%	$(\text{Number of measures implemented} / \text{Total number of planned measures within the community}) \times 100\%$

Table 2. Continued

No.	Indicator	Unit	Baseline (2023)	Target	Calculation formula
Economic component (K)					
8	Water losses in supply networks	%	44%	2030: 30% 2040: 20% 2050: 12%	$(\text{Volume of water lost} / \text{Total volume of water supplied to the network}) \times 100\%$
9	Proportion of reused and recycled water in industry	%	1%	2030: 25% 2040: 45% 2050: 65%	$(\text{Volume of reused water} / \text{Total volume of water used in industry}) \times 100\%$

Source: developed by the authors

The baseline indicators for 2023 highlight several critical issues, including a high level of water losses (44%) and a low rate of stormwater treatment (10%). At the same time, there are positive parameters, such as a wastewater treatment rate of 97% and access to a centralised water supply at 76.85%. The target indicators for 2050 aim to increase stormwater treatment to 90%, reduce water losses to 12%, and raise the share of reused water to 65%, aligning with EU standards and the UN SDGs.

To enable a comprehensive assessment of the effectiveness of water resource management at the territorial community level and support evidence-based decision-making, a multi-level system of indicators has been developed (Fig. 1). The integral indicator of water resource management effectiveness brings together all levels and categories of assessment into a single system, providing a general evaluation of water resource governance within the territorial community.

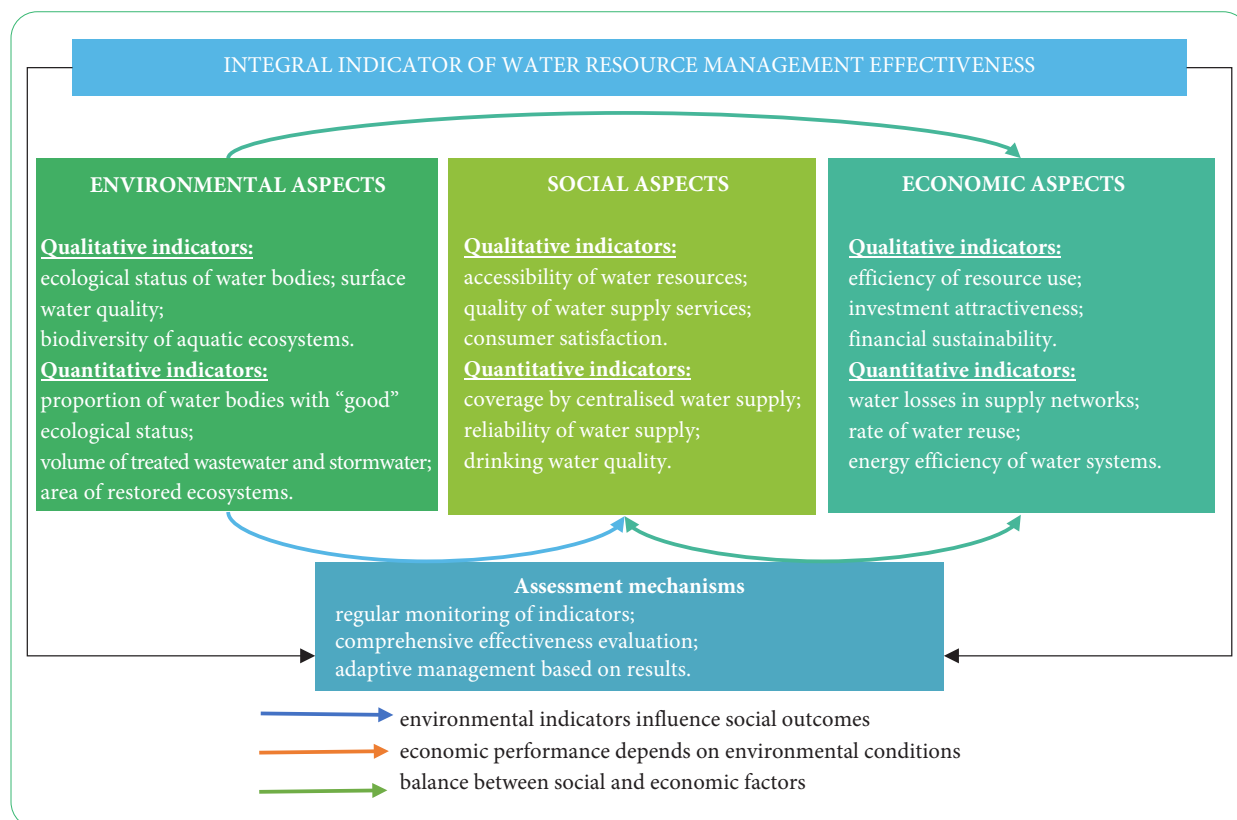


Figure 1. Multi-level indicator system for assessing the effectiveness of water resource management in the Zhytomyr urban territorial community

Source: developed by the authors

Figure 1 illustrates the structure of the multi-level indicator system for assessing the effectiveness of water resource management in the Zhytomyr urban territorial community. The system comprises three main components – environmental, social and economic – each of which is constructed from a set of relevant indicators. Each component includes both qualitative and quantitative indicators.

Environmental qualitative indicators include the ecological status of water bodies, surface water quality, and biodiversity of aquatic ecosystems, while the quantitative ones comprise the proportion of water bodies with “good” ecological status, volume of treated wastewater, and area of restored ecosystems. Social qualitative indicators address accessibility of water resources, quality of water supply services, and

consumer satisfaction, whereas the quantitative ones cover coverage by centralised water supply, reliability of water supply, and drinking water quality. Economic qualitative indicators relate to efficiency of resource use, investment attractiveness, and financial sustainability, while the quantitative ones include water losses in supply networks, rate of water reuse, and energy efficiency of the systems. Additionally, the interrelations between indicators are presented – the influence of environmental indicators on social factors, the dependency of economic aspects on environmental

conditions, and the balance between social and economic dimensions – as well as evaluation mechanisms, including regular indicator monitoring, comprehensive performance assessment, and adaptive management based on outcomes. This indicator system reflects an integrated approach to assessing the effectiveness of water resource management at the level of the territorial community. To calculate the integrated performance indicator, all individual indicators were first normalised using formulas (1) and (2). The results of this normalisation are presented in Table 3.

Table 3. Results of indicator normalisation for the assessment of water resource management effectiveness

Component	Indicator	Actual value, %	Normalised value
Environmental	Proportion of wastewater treated	97	0.97
Environmental	Proportion of water bodies with delineated water-protection zones	0	0
Environmental	Proportion of stormwater treated	10	0.1
Environmental	Proportion of surface-water bodies with “good” ecological and chemical status	0	0
Social	Level of access to centralised wastewater services	87	0.87
Social	Proportion of the population with access to a centralised water supply	89.8	0.898
Social	Level of implementation of the River Basin Management Plan (RBMP) measures within the community’s territory	0	0
Economic	Water losses in supply networks	44	0.56 (inversion: 1-0.44)
Economic	Proportion of reused and recycled water in industry	1	0.01

Source: developed by the authors

The weighting coefficients for the main components of the integrated indicator – environmental, social, and economic – are 0.35, 0.35, and 0.30, respectively. The equal weighting of the environmental and social components reflects their equal importance, aligning with the concept of sustainable development, which emphasises the need to balance environmental, social, and economic dimensions. The methodology for determining these weights through expert consultation is consistent with the approach used by S. Bilalova *et al.* (2023) in assessing the effectiveness of integrated water resources management implementation. This approach allows for the consideration of the priorities of various stakeholders and ensures a balanced assessment. The environmental component was calculated using formula (4) as the sum of the weighted normalised values of the indicators:

$$E = 0 \times 0.35 + 0 \times 0.35 + 0.1 \times 0.3 = 0.03, \quad (7)$$

where 1st 0 – the normalised value of the indicator “Proportion of water bodies with delineated water-protection zones”; 2nd 0 – the normalised value of the indicator “Proportion of surface-water bodies with “good” ecological and chemical status”; 0.1 – the normalised value of the indicator “Proportion of stormwater treated”; 0.35, 0.35, and 0.3 – the weighting coefficients for the respective indicators. The social component was determined using formula (5):

$$S = 0.87 \times 0.4 + 0.898 \times 0.3 + 0 \times 0.3 = 0.6174, \quad (8)$$

where 0.87 – the normalised value of the indicator “Level of access to centralised wastewater services” 0.898 – the normalised value of the indicator “Proportion of the population with access to centralised water supply”; 0 – the normalised

value of the indicator “Level of implementation of the RBMP measures” 0.4 and 0.3 – the weighting coefficients for the respective indicators. The economic component was calculated using formula (6), taking into account the specific method of normalising the indicator for water loss:

$$K = 0.56 \times 0.4 + 0.01 \times 0.3 + 0.97 \times 0.3 = 0.518, \quad (9)$$

where 0.56 – the normalised value of the indicator “Water losses in supply networks” (inversion: 10.44); 0.01 – the normalised value of the indicator “Proportion of reused and recycled water in industry”; 0.97 – the normalised value of the indicator “Proportion of wastewater treated”; 0.4 and 0.3 – the weighting coefficients assigned to the respective indicators. The results of the calculation of the components of the integrated indicator of water resources management efficiency in the Zhytomyr urban territorial community are visualised in Figure 2.

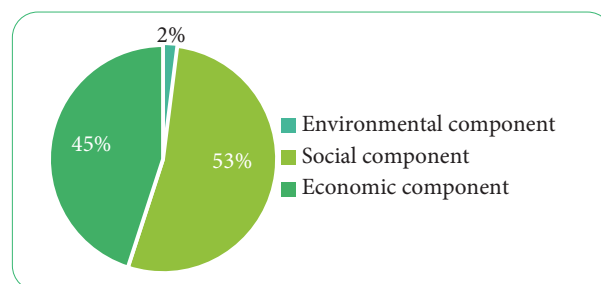


Figure 2. Proportions of the components of the integrated indicator of water resources management efficiency in the Zhytomyr urban territorial community, 2023

Source: developed by the authors

A detailed analysis of the structural elements revealed a critical imbalance in the development of different aspects of the water resource management system. The environmental dimension demonstrated critically low results (0.03), primarily due to the complete absence of legally defined protective water zones – none of the water bodies have formally established boundaries for protection. Additionally, the ecological condition of water bodies is unsatisfactory, with no surface water masses classified as having a “good” ecological status, and surface runoff treatment is inadequate, covering only 10% of the total stormwater volume. The social component showed relatively satisfactory results (0.6174), attributed to the high level of access to centralised water supply systems, providing quality drinking water to 89.8% of the community’s population, and the significant coverage of wastewater services, which are available to 87% of residents. However, the overall score of the social component is negatively affected by the complete lack of implementation of the measures outlined in the River Basin Management Plan, with a current execution rate of 0%. The economic component (0.518) reflects a moderate level of performance. Nevertheless, it is adversely influenced by significant water losses in distribution networks, amounting to 44% of the total volume supplied, and by the minimal level of water reuse in industry, which stands at just 1% of overall industrial water consumption.

In contrast, the high level of wastewater treatment – 97% of total wastewater entering treatment facilities – positively contributes to the economic component score.

The critically low result for the environmental component (0.03) aligns with the findings of H. Kireitseva *et al.* (2024), who identified similar issues in other communities within the Zhytomyr Region. The high rate of water loss (44%) exceeds the average levels reported for cities in Eastern Europe and requires urgent attention – an issue also confirmed by the research of I. Kapelista *et al.* (2024). In the final stage, the integrated indicator was calculated using formula (3), applying the respective weighting coefficients for each component:

$$I = 0.03 \times 0.35 + 0.6174 \times 0.35 + 0.518 \times 0.3 = 0.382. \quad (10)$$

The calculations carried out indicate that the composite indicator of water resource management performance stands at 0.382, which reflects a level of efficiency below the average benchmark. This result highlights the existence of significant potential for improving the system of integrated water resource management within the studied territorial community. Based on the target values of indicators for 2030, 2040 and 2050, a model of the projected dynamics of the integrated efficiency indicator was developed using formulas (1-6). The results of this modelling are presented in Table 4.

Table 4. Projected dynamics of the integrated indicator of water resource management efficiency

Year	Environmental component	Social component	Economic component	Integrated indicator
2023	0.03	0.6174	0.518	0.382
2030	0.648	0.883	0.725	0.749
2040	0.799	0.927	0.875	0.867
2050	0.925	1.000	0.965	0.963

Source: developed by the authors

Scenario planning for the period up to 2050 demonstrates the potential to achieve a high level of efficiency (0.963) provided that all planned measures are comprehensively implemented. The stepwise improvement of indicators involves three main stages of system development. The period 2023-2030 is characterised by the most intensive growth, with the integrated indicator projected to reach 0.749, driven primarily by significant progress in the environmental component, which is expected to increase to 0.648. This growth will result from the planned demarcation of protective buffer zones for all water bodies in the community. The subsequent 2030-2040 phase may be regarded as a period of system stabilisation, during which the integrated indicator is projected to reach 0.867, with steady improvements expected across all components of water resource management. The final optimisation phase (2040-2050) anticipates achieving a level of 0.963, aligning with best international practices in water management. This includes reaching the maximum value (1.000) for the social component.

To improve the effectiveness of integrated water resource management in the Zhytomyr urban territorial community, priority attention should be given to three key areas: environmental aspects of water use, including the delineation of water protection zones and the modernisation of stormwater

treatment systems to enhance the quality of water bodies; economic optimisation of the system through the reduction of water losses in distribution networks and the implementation of water recycling technologies in industrial processes; and enhancement of the social component by increasing the level of implementation of basin management measures and ensuring universal access to quality water supply and sanitation services. The results obtained are consistent with research findings that underscore the need for a comprehensive approach to urban water management and the integration of various aspects of water resource governance.

An in-depth analysis of water resource management effectiveness indicates that the proposed multilevel indicator system aligns with approaches developed in the research by M. AbdiDehkordi *et al.* (2021), who proposed a composite water resource resilience index that accounts for various components, including reservoir conditions and inter-basin water transfers. This approach enables the assessment of not only the current state but also the development potential of water resource management systems. The environmental component, which proved to be the most critical issue for the Zhytomyr community (0.03), can be significantly improved through the adoption of strategies proposed by J.C. Ferreira *et al.* (2024), who examined the

effectiveness of integrating blue-green infrastructure into water management systems. This approach is particularly relevant for urban areas with high population density and limited opportunities for the expansion of traditional “grey” infrastructure. Notably, the findings of B. Essex *et al.* (2020) on global solutions for integrated water resource management in cities around the world highlight the importance of accounting for local specificities when implementing universal approaches. This is particularly relevant for the Zhytomyr community, which faces specific challenges such as a high level of water loss (44%) and a low level of storm-water treatment (10%). The evaluation of the economic efficiency of water use, especially in the context of significant distribution losses and low levels of water reuse, aligns with the approaches developed by X. Cao *et al.* (2021), who proposed a methodology for assessing water use efficiency in agricultural production from a water footprint perspective. This methodology could be adapted for the industrial sector of the Zhytomyr community to improve water use efficiency and achieve targeted reuse indicators.

The results of the evaluation of water resource management effectiveness in the Zhytomyr community underscore the importance of a comprehensive approach, as supported by international experience. R. Calipha & S. Katav-Herz *et al.* (2025) demonstrated that the implementation of the EU Water Framework Directive led to a 40% improvement in surface water quality and a 25% reduction in groundwater pollution over a 15-year period – outcomes that may serve as valuable benchmarks for Ukrainian communities in the context of European integration. P. Hellegers & G. Van Halsem (2021) identified methodological shortcomings in SDG indicator 6.4.1, “Change in water-use efficiency over time”, and proposed improvements for further development of indicator systems. Yu. Huseynov *et al.* (2024) analysed 170 water resource management indicators according to four sustainability criteria, using the DPSIR framework (Drivers, Pressures, States, Impacts, and Responses). This approach is particularly relevant to the Zhytomyr community, where the ecological component is critically low (0.03). The study also highlights the potential for improving assessment schemes through strategic planning of monitoring networks and the use of innovative diagnostic tools – an essential step towards optimising the utilisation of available data within the developed monitoring system. B. Essex *et al.* (2020) proposed a national monitoring framework for water-related SDGs in Europe based on a participatory approach and stakeholder consensus evaluation, which aligns with the expert survey methodology employed in the Zhytomyr community. A common thread across all studies is the recognition of the need for an integrated approach that combines technical solutions with institutional innovation. The effectiveness of water governance is shown to depend heavily on the quality of monitoring and evaluation systems, thereby reinforcing the relevance of the multi-level indicator framework that has been developed.

Also noteworthy is the study by J.Y. Al-Jawad *et al.* (2019), which outlines an optimal integrated approach to

water resource management aimed at addressing multidisciplinary challenges. This approach – incorporating social, environmental, and economic dimensions – corresponds to the structure of the proposed multi-tiered indicator system. The study employed mathematical optimisation models to balance the competing demands of different water users, resulting in a 25% improvement in resource allocation efficiency and a 30% reduction in conflicts between water-use sectors. The methodological approach of the study is particularly valuable in that it takes into account the uncertainty associated with forecasting water resources and incorporates adaptive management mechanisms – an aspect that is critically important in the context of climate change and increasing anthropogenic pressure on aquatic ecosystems. A similar approach to the comprehensive analysis of urban water management was demonstrated by B. Essex *et al.* (2022) in their study of global challenges in integrated water resources management in cities worldwide. The authors analysed 200 cities representing over 95% of the world’s urban population, applying the City Blueprint Approach for an empirical assessment of 125 cities and a statistical model to evaluate water governance performance in a further 75. The study revealed significant gaps in achieving water-related SDGs, particularly Goals 6 and 11. It emphasised that addressing water challenges can serve as a gateway to meeting other SDG targets, given that water is directly or indirectly linked to nearly all of them. A regional approach to indicator development is presented in the study by M. Ben-Daoud *et al.* (2021), which proposed an indicator framework for integrated water resources management to assess governance systems in the Rdom sub-basin in Morocco. A comprehensive methodology was developed encompassing ecological, social, economic, and institutional dimensions, validated through an international expert panel. The study utilised the DPSIR framework to classify all indicators, enabling a holistic analysis of causal relationships within the water management system.

It is worth noting that the greatest progress in improving the effectiveness of water resources management is expected in the ecological dimension, where the indicator is projected to rise from 0.03 in 2023 to 0.925 by 2050. Such growth is achievable, provided that a comprehensive set of measures is implemented, aimed at improving the ecological condition of water bodies, establishing water protection zones, and increasing the level of stormwater treatment. To assess the effectiveness of these measures, the approaches proposed by J. Katusiime and B. Schütt (2020) may be applied, highlighting the importance of institutional mechanisms and strategic frameworks for the successful implementation of integrated water resource management. The analysis also shows that the social dimension of water management effectiveness currently records the highest score (0.798) among the three components. This is attributed to the high level of access to centralised water supply and sanitation services in the Zhytomyr community. However, in order to achieve the maximum level of effectiveness (1.000) by 2050, it is necessary to ensure 100% population access to quality water supply and wastewater services, as

well as the full implementation of the measures outlined in the River Basin Management Plan (Pripyat River Basin Water Resources Management, 2023).

The economic component of water management effectiveness in the Zhytomyr community (0.518) requires substantial improvement, particularly in reducing water losses in distribution networks and increasing the rate of water reuse in industry. Meeting the target indicators – reducing water losses to 12% and increasing the share of reused water to 65% – will require significant investment in infrastructure modernisation and the adoption of water-saving technologies. The importance of economic efficiency in water resource use was also emphasised in the study by N.R. Gayathri *et al.* (2024), who developed an intelligent system for monitoring and managing water quality, enabling the optimisation of water use and the reduction of operational costs.

Thus, the proposed integrated system for assessing the effectiveness of water resource management in communities allows for a comprehensive evaluation of the current state of the management system, identification of critical areas requiring priority attention, and forecasting of the system's development dynamics, provided the necessary measures are implemented. This system can be adapted for use in other territorial communities in Ukraine, taking into account their specific features and challenges in water resource management. The developed system of indicators and the integrated approach to evaluating water management effectiveness provide a methodological foundation for monitoring and assessing progress in achieving the SDGs at the territorial communities level. They also offer tools for informed decision-making and the development of water management strategies that consider the economic, social, and environmental dimensions of water use. Furthermore, the proposed approach enables comparative analysis of water management effectiveness across different territorial communities, laying the groundwork for knowledge exchange and the adoption of best practices.

✓ Conclusions

The conducted study on the integrated monitoring system for assessing the performance of water management activities at the level of territorial communities allows for the following general conclusions. The developed methodological framework for analysing the effectiveness of community water management integrates environmental, social, and economic dimensions into a comprehensive indicator, providing a tool for diagnosing problem areas and supporting evidence-based decision-making. The monitoring system

comprises nine interrelated indicators across the three pillars of sustainable development, ensuring a comprehensive assessment of water management performance. The use of the expert method to determine weighting coefficients ensured that the priorities of various management vectors were taken into account.

Empirical testing of the methodological tools using data from the Zhytomyr community revealed significant imbalances in the functioning of different components of the management system. The environmental dimension requires the most urgent attention, with its indicator value at just 0.03, reflecting the absence of legally defined water protection zones and the poor condition of surface water bodies. The social dimension, with an indicator value of 0.6174, demonstrated comparatively better outcomes due to the high level of population coverage by centralised water supply and sanitation services. The economic dimension (0.518) was characterised by moderate performance.

Forward-looking modelling to 2050 indicates the potential for a substantial improvement in management effectiveness, reaching a level of 0.963, provided that the established target values for all indicators are achieved. The most rapid progress is expected between 2023 and 2030, particularly in the environmental dimension, following the designation of water protection zones for all water bodies in the community and an increase in the treatment rate of stormwater to 30%. The developed indicator system and the comprehensive approach to evaluating water management performance form a methodological basis for monitoring and analysing progress towards the SDGs at the level of territorial communities. The proposed approach also enables comparative analysis of water management efficiency across different territorial communities, providing a foundation for knowledge exchange and the implementation of best practices. Areas for further research include expanding the proposed methodology to other territorial communities in Ukraine to validate the universality of the indicator system, as well as developing an automated monitoring system using IoT technologies to ensure real-time data collection.

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Інтегральна оцінка ефективності управління водними ресурсами громад для сталого розвитку

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✓ **Анотація.** Актуальність дослідження зумовлена необхідністю розробки комплексних систем моніторингу для оцінки ефективності управління водними ресурсами, що враховують екологічні, соціальні та економічні аспекти. Метою дослідження було проаналізувати та оцінити існуючі підходи до формування інтегральної системи моніторингу ефективності управління водними ресурсами на рівні територіальних громад для забезпечення екологічної безпеки та сталого розвитку. Дослідження ґрунтувалося на системному підході з використанням SWOT-аналізу, порівняльного аналізу та моделювання. На основі аналізу наукової літератури було розроблено багаторівневу систему показників, що включає 9 ключових індикаторів, згрупованих за екологічною, соціальною та економічною складовими. Розрахований інтегральний показник ефективності управління водними ресурсами становить 0,382, що відповідає нижчому за середній рівню ефективності. Аналіз складових виявив критичний дисбаланс: екологічна складова має критично низький рівень (0,03), що зумовлено відсутністю визначених водоохоронних зон (0 %) та незадовільним станом водних об'єктів (0 % об'єктів з «добрим» станом). Соціальна складова показала відносно високий результат (0,6174) завдяки високому рівню забезпеченості централізованим водопостачанням (89,8 %) та водовідведенням (87 %). Економічна складова (0,518) характеризується середнім рівнем ефективності, але негативно впливають високі втрати води в мережах (44 %) та низький рівень повторного використання води (1 %). Прогностичне моделювання на період до 2050 року показало можливість досягнення високого рівня ефективності (0,963) за умови комплексної реалізації заходів за всіма напрямками, з найбільш динамічним зростанням у 2023-2030 роках. Практична цінність дослідження полягає у формуванні науково обґрунтованої основи для оцінки ефективності управління водними ресурсами на рівні територіальних громад, що дозволяє визначати пріоритетні напрями вдосконалення системи для прийняття обґрунтованих управлінських рішень у сфері водного господарства

✓ **Ключові слова:** оцінювання; екологічна безпека; моніторинг; територіальні громади; індикатори якості; басейновий підхід



Assessment of anthropogenic transformation of groundwater recharge conditions in urban areas

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✓ **Abstract.** A strategic priority for the sustainability of urban areas under climate change is the development of resilient and diversified water supply systems, as the altered urban hydrological cycle disrupts precipitation patterns and the overall water balance. In this context, spring water becomes increasingly valuable, yet the natural recharge of shallow aquifers is threatened by built-up development, changes in soil properties, and the loss of regulating ecosystem services. This study was focused on assessing the degree of anthropogenic transformation of groundwater recharge conditions within the urban areas of Kharkiv, where approximately 30 equipped springs are actively used by the population for drinking purposes. The article examined the extent of anthropogenic alteration of precipitation infiltration conditions in the urban area for three representative springs in Kharkiv (Park Yunist, Oleksiivske, and Hlybokyi Yar), using geospatial analysis. It was found that in typical low-rise residential areas, impervious surfaces constitute up to 29% on average, while in multi-storey residential zones they reach approximately 40% of the total area, owing to the greater space occupied by roads and rooftops. Based on these ratios, it was estimated that impervious surfaces occupy between 17% and 43% of the catchment areas of the studied springs. The findings implied a significant reduction in the natural recharge of aquifers due to the impeded infiltration on impervious surfaces. Direct measurements of the springs' discharge confirmed that the hydrodynamic regime of the springs is affected not only by the proportion of surface types but also by the technical condition of capture facilities, additional recharge from leaking water supply networks,

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and the structure of the aquifers. The proposed methodological approach and the results obtained are of high practical importance for local authorities in planning and developing adaptation measures for urban water supply systems in the context of climate change and other environmental challenges and threats

✔ **Keywords:** sustainable development; urban water use; springs; impervious surfaces; infiltration; geospatial analysis

✔ Introduction

A sustainable water supply in urban areas is one of the most pressing issues, which has become increasingly acute due to the impacts of urbanisation, demographic growth, and climate change, particularly since the late 20th century. The expansion of urban areas and a rise in population density in cities inevitably lead to increased demand for water resources, as well as impacts on surface and groundwater sources. Drinking water quality issues in large Ukrainian cities can be addressed through the rational use of groundwater and the implementation of combined water supply systems, as demonstrated in the research by O. Bondar *et al.* (2021). Under favourable hydrogeological conditions, groundwater offers specific advantages, making it a valuable resource for urban water supply. In particular, these include better protection from contamination due to natural filtration through soils and rocks, according to M.S. Siddik *et al.* (2022), reduced susceptibility to seasonal fluctuations and short-term meteorological changes; and lower evaporation losses compared to surface sources, which is especially relevant in the context of climate change, as discussed in the study by P.U. Dao *et al.* (2024). Groundwater has been shown to be more resilient to climate change than surface sources, and aquifers may provide a stable water supply during climate-induced fluctuations, as investigated by M. Filippini *et al.* (2024). Despite the considerable potential of groundwater for urban water supply, its efficient utilisation faces several challenges in the context of climate change and urbanisation, due to land-use changes, overexploitation, and pollution from various sources, as highlighted by F. Parvin *et al.* (2024).

Urbanisation significantly impacts the hydrological cycle in urban areas, altering the water balance and conditions for the redistribution of precipitation, groundwater, and surface water. According to M. Feltynowski & J. Kronenberg (2020) and B.A. Yifru *et al.* (2022), the area of impervious surfaces – which alter the pathways of precipitation migration – ranges from 30% to 70% of the territory of large cities. Significant changes in surface runoff formation occur when the total impervious area reaches between 10% and 15%. As evidenced by J.R. Avila-Carrasco *et al.* (2023), when impervious surfaces exceed 30% of the total area, a critical shift in the hydrological regime of water bodies is observed. The infiltration capacity of urban soils also differs significantly from that of natural environments. A. Riaz *et al.* (2025) noted that urban soil compaction can reduce the infiltration rate by 20-60% compared to natural soils. Chemical pollution causes hydrophobicity, degradation of soil structure, and reduced microbiological activity, all of which affect macropore formation and maintenance, there

by reducing infiltration capacity by up to 25%. E.A.O. Serão *et al.* (2022) found that these changes lead to increased surface runoff, a heightened risk of flooding in densely urbanised areas, a 2-5-fold reduction in infiltration capacity compared to forest soils, and up to a 50% reduction in urban groundwater recharge.

J. Dutta *et al.* (2024) argued that urban areas are also subject to additional anthropogenic recharge, formed due to leakages from centralised water supply and sewerage networks. The volume of this recharge in large cities has been found to be two to five times greater than natural infiltration. The complexity of urban water balance alterations increases when inter-basin water transfers occur to meet demand, as is the case in Kharkiv. The issue of anthropogenic impacts on infiltration recharge is compounded by the direct effects of climate change – particularly shifts in precipitation seasonality and intensity, and increased evaporation – as discussed by Q. Zhang *et al.* (2020). Kharkiv's water supply system relies primarily on surface water and, to a lesser extent, on artesian groundwater, with spring water serving as an additional source. The city has up to 30 equipped springs, which are in high demand among the population, especially during wartime, when the centralised water supply system may malfunction. In urbanised areas, shallow aquifers discharged by springs are most vulnerable to anthropogenic impacts, including altered infiltration recharge. As highlighted in the above literature, the methodological and practical aspects of assessing such impacts – and their implications for groundwater balance in urban environments – remain insufficiently studied, particularly in Ukrainian cities.

This study aimed to assess the degree of anthropogenic transformation of groundwater infiltration conditions within urban development areas, using the city of Kharkiv as a case study. To achieve this aim, a methodological approach was developed to determine the ratio of permeable to impervious surfaces in typical built-up urban areas of Kharkiv; to calculate the area and proportion of these surfaces within the catchment zones of urban springs; and to assess the degree of transformation of groundwater recharge conditions in built-up areas.

✔ Materials and Methods

The distribution of different building types in the city of Kharkiv was analysed based on open vector geodata from OpenStreetMap (2025). Owing to favourable hydrogeological conditions, Kharkiv is characterised by an abundance of natural springs – more than 30 in total. These springs represent groundwater outflows to the surface, with a wide range

of flow rates from 0.3 to 38 dm³/s. They are equipped and frequently used by residents for drinking purposes. The aquifers belong to the upper water exchange zone of Cenozoic age and are located at depths of 30–40 m below ground level.

For this study, three urban groundwater springs were selected, as they are among the most popular in Kharkiv and are regularly used by city residents for drinking purposes –

Park Yunist, Oleksiivske, and Hlybokyi Yar (Fig. 1). An analysis of built-up areas was conducted within the catchment zones of these springs. Their configuration and extent were previously delineated by V.V. Yakovlev (2017) using hydrogeological calculations based on long-term average spring flow rates, regional groundwater flow velocity, and the filtration properties of the aquifer.

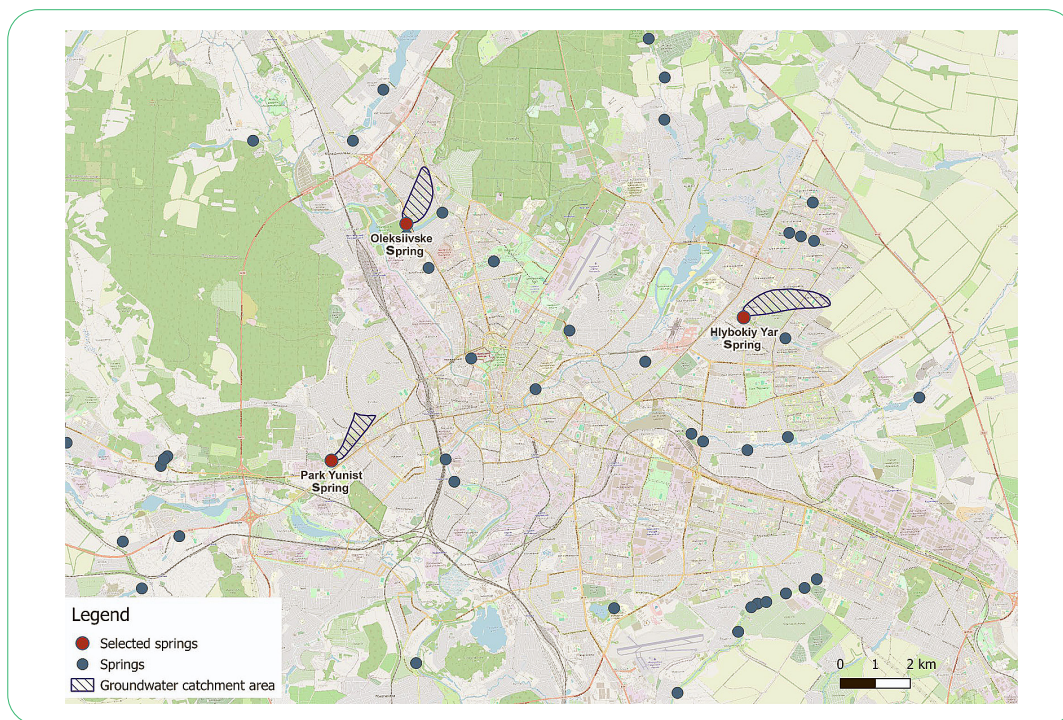


Figure 1. Map showing the location of springs in Kharkiv

Source: created by the authors

Under natural conditions, these springs are recharged by precipitation infiltration across the entire aquifer area. The Park Yunist Spring is located on the left bank of the Udy River valley. The aquifer consists of alluvial and alluvial-deluvial sandy deposits of Quaternary and Pliocene age. The spring capture structure includes four stainless steel pipes embedded in a concrete retaining wall, which ensures uniform water intake (Fig. 2). The Oleksiivske Spring is situated in the Oleksiivska Arroyo, on the left bank of the Lopan

River valley. The capture comprises 12 stainless steel pipes installed in two retaining walls, supplying water from two intake wells located on both sides of the arroyo. This aquifer is composed of Obukhiv fractured siltstones. The Hlybokyi Yar Spring is located on the right-hand slope of the Hlybokyi Yar Arroyo, in the Kharkiv River valley. Its capture includes a water intake well and six distribution pipes fitted with a canopy. This spring also belongs to the Obukhiv aquifer, which consists of fractured siltstones and fine-grained sandstones.

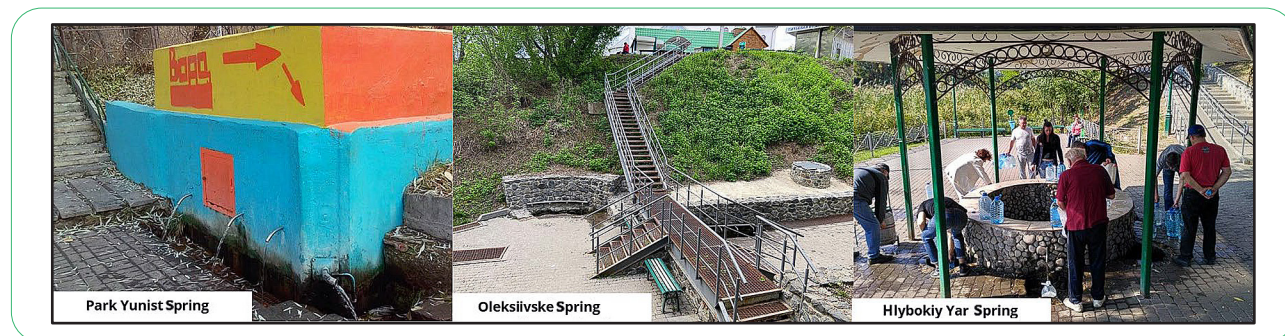


Figure 2. General view of the studied springs

Source: created by the authors

The hydrodynamic regime of shallow aquifers is determined, among other factors, by the permeability of soil surfaces in the aquifer recharge zone. A reduction in precipitation infiltration due to the presence of impervious surfaces inevitably affects spring flow rates. To reveal possible links between these factors, the water flow rate (discharge) of the springs was measured monthly from 2018 to 2021. The measurements were carried out on site using the volumetric method, with a measuring container (5-6 litres) and a stopwatch. The time taken to fill the container was measured to the nearest second. For springs with multiple outlets, each outlet was measured separately; the values were then summed and converted into litres per second (L/s). To determine the areas of permeable and impervious surfaces in the study area, the open-source geographic information system QGIS 3.38.0 (2024) was used.

The research was carried out in several stages. In the preparatory stage, basemap layers from OpenStreetMap (2025) and high-resolution satellite imagery from Microsoft Bing (2025) and Google Maps (2025), covering multiple seasons, were accessed and integrated. During the pilot site selection stage, two representative areas with multi-storey residential and private low-rise residential buildings were selected near each studied spring (six sites in total). In the vectorisation stages, vector polygon boundaries were delineated for the pilot sites, built-up areas, road surfaces (streets, pavements, parking areas), and green spaces (bare ground, lawns, parks). The vector outlines were refined using OpenStreetMap (2025) data, and where data were missing or incomplete, new boundaries were digitised based on satellite imagery. Vectorisation was performed with an estimated accuracy of up to 5 m². To ensure correct area representation, buildings were vectorised along the contour of the foundations to minimise errors caused by satellite image angles. Some degree of uncertainty

remained in multi-storey built-up areas, where adjacent roads and pavements were partially shaded or obscured by tree canopy and could not be identified with maximum accuracy. In the database creation stage, a geodatabase was developed containing the vectorised features and their attributes. During the area calculation stage, the permeable and impervious surface areas for each site were calculated based on the vector data. Impervious surfaces included building roofs and road surfaces, while permeable surfaces comprised all other types. In the ratio analysis stage, the average proportions of permeable and impervious surfaces were identified for each type of built-up area. In the final stage, the derived ratios were applied to the springs' catchment areas to determine the total proportion of impervious surfaces in the catchment of each spring. This methodological approach optimised the research process by focusing on detailed vectorisation of limited representative areas, rather than comprehensive vectorisation of the entire catchment zones. This strategy significantly reduced the time and effort required while maintaining sufficient accuracy.

✓ Results and Discussion

Geospatial analysis has shown that the city of Kharkiv is characterised by a variety of built-up area types. Multi-storey and private low-rise residential buildings dominate the urban landscape, together accounting for 42% of the total area. In addition, transport infrastructure – including roads, car parks, and garages – occupies 23% of the territory. A significant proportion of the city (21%) consists of green areas, while industrial (11%) and commercial (3%) buildings play a comparatively minor role in the urban landscape. Based on the vectorisation results from the pilot sites in Kharkiv, quantitative data on the distribution of permeable and impervious surfaces in areas with different types of development were obtained (Table 1).

Table 1. Areas of permeable and impervious surfaces at pilot sites with multi-storey and private low-rise residential buildings

Building type	Name of the spring	Total area of the pilot site, ha	Surface area, ha		Share of the total area, %	
			impervious	permeable	impervious	permeable
Private low-rise residential	Hlybokyi Yar	26.38	6.14	20.24	23.3	76.7
	Oleksiivske	5.63	1.83	3.79	32.6	67.4
	Park Yunist	10.16	3.14	7.02	30.9	69.1
Multi-storey residential	Hlybokyi Yar	62.49	23.62	38.88	37.8	62.2
	Oleksiivske	12.01	4.84	7.17	40.3	59.7
	Park Yunist	22.52	9.49	13.02	42.2	57.8

Source: created by the authors

Analysis of the obtained data showed that in private low-rise residential areas, permeable surfaces occupy between 67.4% and 76.7% of the total area (with an average of 71%), while impervious surfaces vary from 23.3% to 32.6% (average: 29%). In multi-storey residential areas, the proportion of permeable surfaces ranges from 57.8% to 62.2% (average: 60%), and impervious surfaces range from 37.8% to 42.2% (average: 40%). In private low-rise residential areas, impervious surfaces are mainly represented by the roofs

of private houses and household outbuildings on private plots (8.7%-22.2% of the total area), as well as roads and pavements (8.8%-14.6%). In multi-storey residential areas, impervious surfaces include the roofs of multi-storey buildings (13.5%-19.0%) and a significantly larger share of road surfaces (21.3%-24.3%), comprising internal access roads, pavements along building entrances, and asphalted adjacent areas. Figure 3 shows images of the pilot site near the Hlybokyi Yar Spring, before and after the vectorisation

of permeable and impervious surfaces. The multi-storey residential area is predominantly composed of typical 9-, 12-, and 16-storey buildings. The low-rise area consists of

residential houses and various outbuildings (sheds, canopies, garages, saunas, etc.), which are commonly found across all the studied plots within the city.

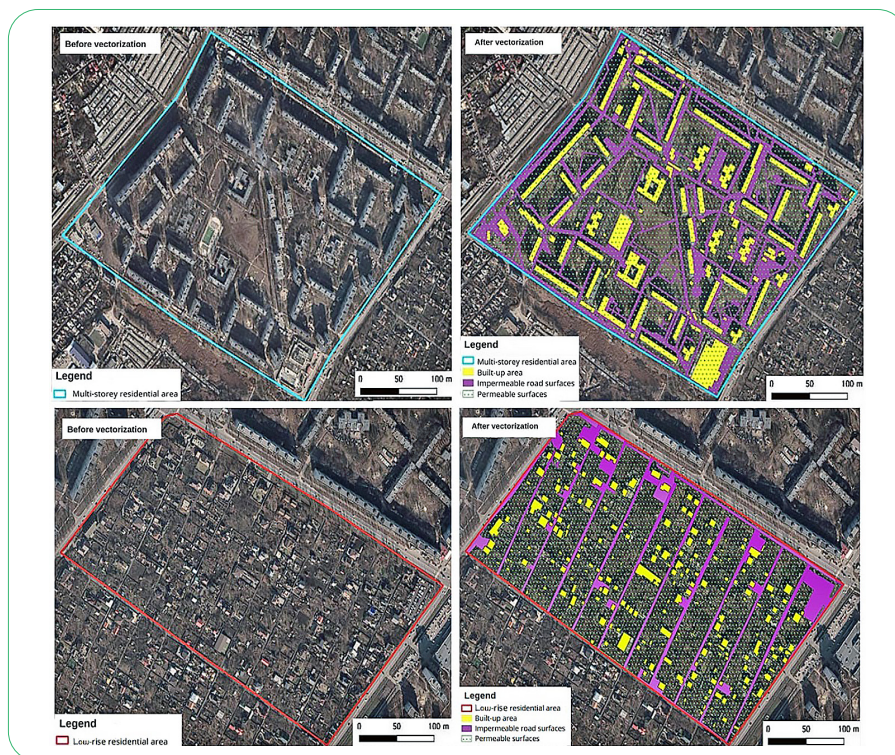


Figure 3. Pilot site near the Hlybokyi Yar Spring

Source: created by the authors

Figure 4 shows images of the vectorised surfaces at the pilot site located near the Oleksiivske Spring. The multi-

storey residential area includes five-storey buildings as well as several high-rise buildings exceeding 12 storeys.

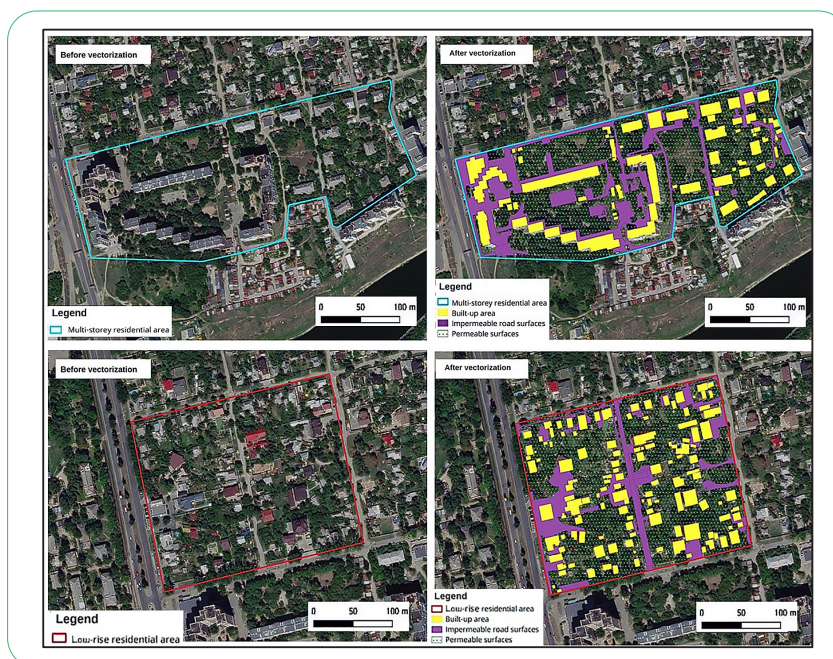


Figure 4. Pilot site near the Oleksiivske Spring

Source: created by the authors

The vectorised surfaces at the pilot site near the Park Yunist Spring are shown in Figure 5. This area features nine- and twelve-storey residential buildings, alongside three-storey social infrastructure buildings (schools, kindergartens) within the same area. Despite variations in the total area of the pilot plots, the proportions of permeable and impervious surfaces for the two analysed types of development did not differ significantly, particularly in the case of multi-storey residential areas. Therefore, both types of residential development may be considered typical across the city of Kharkiv. The derived ratios of permeable and impervious surfaces for private low-rise and

multi-storey residential areas are likely to be representative of other city districts. These results make it possible to apply the average values of surface shares for rapid assessments in other urban areas without the need for time-consuming and labour-intensive vectorisation procedures. The studied springs' catchment zones varied in size from 54.5 to 124.6 ha, depending on spring discharge and hydrogeological conditions, as defined by V.V. Yakovlev (2017). Classification of satellite imagery has shown that each spring has a distinct ratio of private low-rise, multi-storey residential, and green areas within its catchment (Table 2).



Figure 5. Pilot site near the Park Yunist Spring

Source: created by the authors

Table 2. Distribution of different built-up area types within the springs' catchment zones

Name of the spring	Total area of the spring's catchment zones, ha	Multi-storey residential area		Private low-rise residential area		Green area	
		ha	%	ha	%	ha	%
Hlybokyi Yar	124.6	104.2	83.6	17.1	13.7	3.3	2.6
Oleksiiivske	83.4	50.3	60.3	33.1	39.7	0	0
Park Yunist	54.5	32.1	58.9	11.0	20.0	11.4	20.9

Source: created by the authors

The catchment area of the Hlybokyi Yar Spring is predominantly occupied by multi-storey residential development, which is typical for the north-eastern part of the city. This development accounts for approximately 84% of the total catchment area, while private low-rise housing

comprises almost 14%, and green areas occupy less than 3% (Fig. 6). In the catchment of the Oleksiivske Spring, the ratio of multi-storey to private low-rise residential buildings is approximately 60:40, with no green areas identified (Fig. 7).

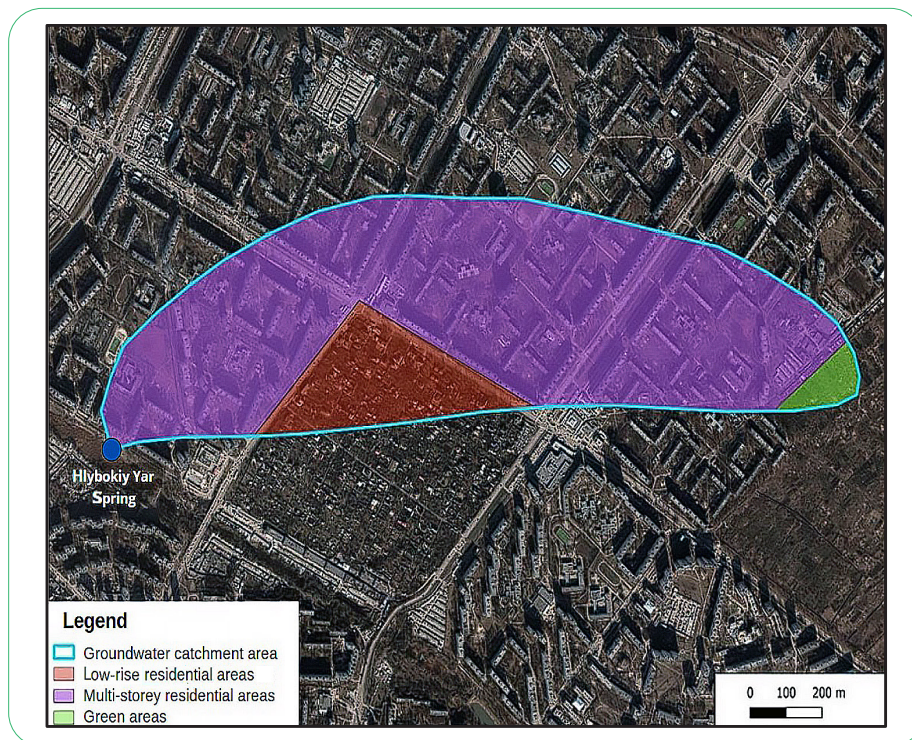


Figure 6. Distribution of built-up areas in the catchment zone of the Hlybokiy Yar Spring

Source: created by the authors

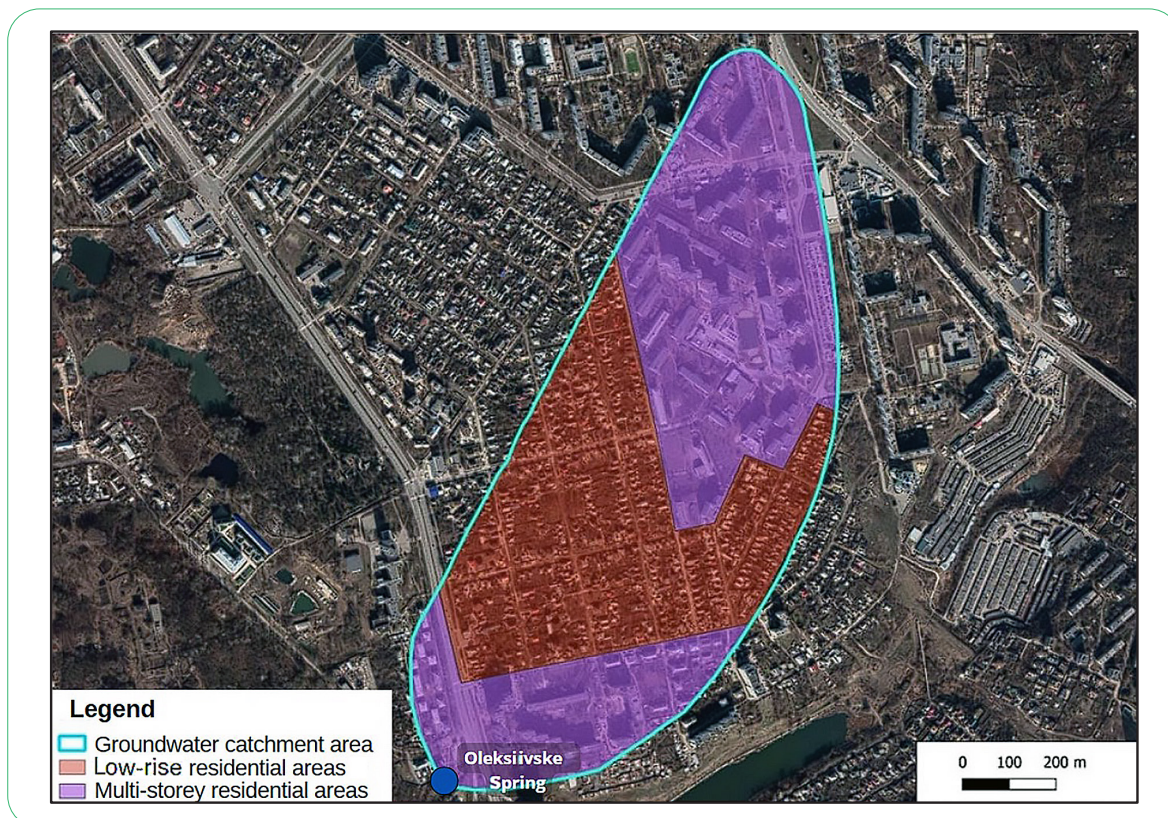


Figure 7. Distribution of built-up areas in the catchment zone of the Oleksiivske Spring

Source: created by the authors

The catchment area of the Park Yunist Spring is characterised by a relatively high proportion of green space

(approximately 21%) but is still dominated by multi-storey buildings, which account for about 60% of the area (Fig. 8).

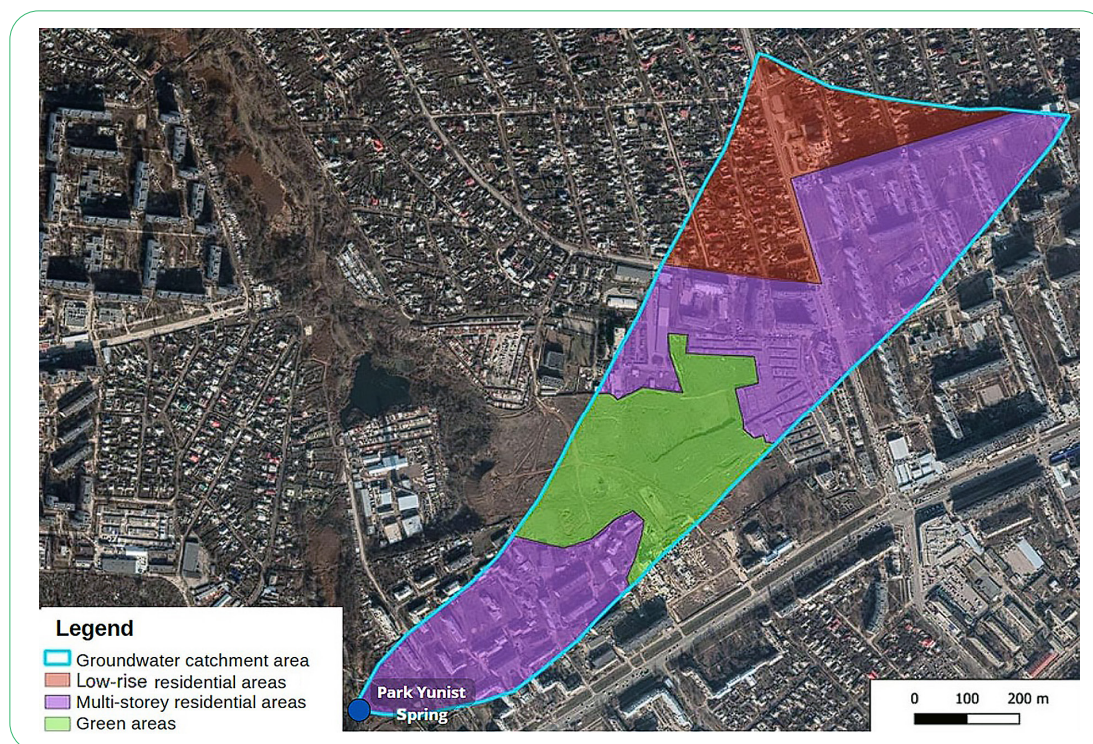


Figure 8. Distribution of built-up areas in the catchment zone of the Park Yunist Spring

Source: created by the authors

According to the present estimates, the actual share of impervious areas due to such features may be 5-10% higher than the vectorisation results obtained from the pilot sites. Based

on the types of development within the catchment zones, the ratio of permeable to impervious surfaces was calculated using the average values for each type of built-up area (Table 3).

Table 3. Distribution of permeable and impervious surfaces in the springs' catchment areas

Name of the spring	Area of the spring's catchment zone, ha	Share of impervious surface area, %	Share of permeable surface area, %
Hlybokyi Yar	124.6	43.3	56.7
Oleksiivske	83.4	33.6	66.4
Park Yunist	54.5	16.9	83.0

Source: created by the authors

The results indicate that the catchment areas of the studied springs are characterised by varying degrees of anthropogenic transformation. The catchment of the Hlybokyi Yar Spring has the highest proportion of impervious surfaces (43.3%) due to the predominance of multi-storey residential development (84% of the area). This suggests the greatest level of transformation of infiltration recharge among the springs under study. The Oleksiivske Spring catchment exhibits a moderate level of anthropogenic transformation, with impervious surfaces accounting for 33.6%. This zone is characterised by a more balanced distribution of multi-storey residential buildings (60.4%) and private low-rise houses (39.6%). The catchment of the Park Yunist Spring has the lowest share of impervious surfaces (16.9%) due to a comparatively higher proportion of green space (21%) and less intensive development. The results of spring discharge measurements, which were conducted regularly over a four-year period, revealed noticeable differences between the springs (Fig. 9).

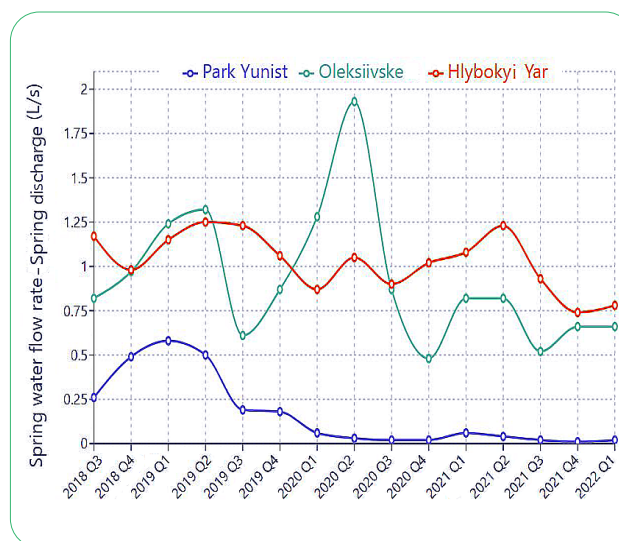


Figure 9. Flow rate of springs

Source: created by the authors

The Hlybokyi Yar Spring is one of the most powerful in the city. The average discharge during the observation period reached up to 1.0 L/s. Over the study period, the flow rate remained relatively stable, fluctuating within the range of 0.8-1.5 L/s. These fluctuations were irregular but may be associated with seasonal variations in groundwater recharge. An increase in recharge from December to April is common in the region due to more intensive infiltration of precipitation during the colder months, as established in previous studies (Vystavna *et al.*, 2018). A reduction in spring discharge from May to October may be attributed to decreased precipitation, particularly lower-intensity rainfall.

The Oleksiivske Spring exhibited the most complex discharge dynamics. Until June 2019, its flow rate remained relatively strong, comparable to that of the Hlybokyi Yar Spring (0.8-1.4 L/s). Subsequently, sharp and uneven changes in discharge were recorded, ranging from 0.6 L/s to 2.0 L/s. In 2021, fluctuations continued but occurred within a relatively stable and lower range of 0.5-0.6 L/s. The survey indicated that the primary factor behind these changes is likely to be additional water abstraction from the intake well for commercial filtration and sale, as well as technical faults in the spring capture facility. The average discharge at the spring over the entire observation period was 1.1 L/s.

The Park Yunist Spring has the lowest flow rate among the studied springs, which can be attributed to the lower capacity of the Quaternary aquifer, located near the surface and characterised by faster water exchange. At the start of the monitoring period, the average flow rate was 0.5 L/s. Since the summer of 2019, there has been a gradual and sustained decline in discharge, reaching 0.020.03 L/s. The most probable cause of this reduction is a failure in the spring's capture structure.

The above findings regarding the impact of impervious surfaces on urban groundwater regimes are consistent with contemporary international research on urbanised areas. For instance, G. Nazari *et al.* (2023) confirmed that urbanisation markedly reduces the potential for groundwater recharge. In highly urbanised watersheds, up to half of the water inflow is diverted from infiltration, doubling the proportion of surface runoff in the urban water budget from approximately 15% to 30%. These data support the argument concerning the critical influence of impervious surfaces on groundwater recharge processes. Furthermore, the trend of expanding built-up areas, which further exacerbates the disruption of urban groundwater recharge, is evident in various global contexts. A study by M. Minnig *et al.* (2018) in Switzerland documented an 80.3% increase in impervious built-up areas, alongside a 16.4% decrease in vegetative cover, reflecting a broader urbanisation pattern in European cities. Similar trends have been observed in Asian cities by M. Ahmad *et al.* (2023), where interactions between groundwater and the urban environment are becoming increasingly significant. These changes impact both recharge and flow, as impervious surfaces reduce infiltration by enhancing surface runoff.

Studies utilising Gravity Recovery and Climate Experiment (GRACE) satellite data (NASA, 2023) from 2003 to 2020 have demonstrated that impervious surfaces limit rainwater infiltration and hinder natural groundwater recharge. However, the present study's measurements of spring discharge suggest that these losses may be partially offset by specific local factors. Notably, leakage from water mains, which is believed to be widespread in Kharkiv and likely in other major Ukrainian cities, may play a compensatory role. This assumption is supported by current research. Indeed, the construction of impervious surfaces and artificial drainage channels accelerates the direct flow of precipitation to streams, thereby bypassing groundwater recharge and accumulation. Nevertheless, the Hlybokyi Yar spring, despite having the highest percentage of impervious surfaces (43.3%), exhibits a relatively high and stable discharge (averaging 1.0 L/s). This may be attributed to its large catchment area (124.6 ha) and specific geological conditions, namely the presence of a locally highly conductive zone in the aquifer (fractured Obukhiv siltstones), as well as a relatively constant input from leaking tap water mains in the multi-storey built-up area that predominates in the catchment. Previous estimations of recharge fractions based on isotopic mixing signatures, conducted by D. Diadin & Y. Vystavna (2020) for this particular spring, revealed a noticeable anthropogenic input from the centralised water supply network – up to 29%. Studies from other locations confirm that leakage from water supply systems can significantly increase localised groundwater recharge, as noted by D. Owen (2021) and in the California Water Plan Update (2024).

Meanwhile, the Oleksiivske Spring, with a moderate 33.6% impervious surface coverage in its catchment, demonstrated the most unstable discharge regime. Observations suggest that this instability is likely influenced by additional factors, such as technical interventions (e.g. water abstraction for commercial use) and structural deficiencies in the spring's infrastructure. The Park Yunist Spring, although having the lowest share of impervious surfaces in its catchment area (16.9%), nonetheless exhibits the lowest discharge among the springs studied. This is primarily due to the relatively lower capacity of its Quaternary sandy aquifer compared to the aquifers of the other springs, its smallest catchment area (54.5 ha), and evident structural issues with the spring capture, particularly observed *in situ* during 2019-2020. Thus, anthropogenic impacts on the capacity of springs as water sources involve not only the alteration of surface permeability and natural recharge but also discharge instability resulting from technical deficiencies and specific patterns of water use.

Another essential aspect of the research is the assessment of spatial heterogeneity in urban environments, a topic explored in various international studies, such as those by L. Chelleri & A. Baravikova (2021). Contemporary strategies for improving urban hydrology categorise interventions into three groups, including “impervious surface-focused strategies” aimed at disconnecting non-porous surfaces from direct drainage systems. The differences

in surface ratios across the studied springs' catchment areas (ranging from 16.9% to 43.3% impervious surfaces) presumably reflect varying levels of pollution risk to spring-fed groundwater. Permeable surfaces in low-rise residential zones may serve as pathways for polluted runoff and irrigation water from private households. Combined with leakage from sewage networks and individual septic systems, these factors are typical of many urban areas with private housing, as shown by F. La Vigna (2022) and V. Tiwari *et al.* (2024). Urban stormwater represents another underestimated pathway for the spread of mixed contaminants into shallow groundwater. For this reason, many researchers, including A.D. Steinman *et al.* (2022) and A. Geraldine *et al.* (2024), emphasised the importance of monitoring and managing the quality of additional anthropogenic recharge.

The study results demonstrate a significant impact of urban development on the recharge conditions of shallow groundwater. According to the data obtained, even in areas dominated by private low-rise residential buildings, up to 30% of the land is occupied by impervious surfaces that impede the natural infiltration of precipitation. In multi-storey residential areas, this share rises to 40%. Such a high proportion of impervious surfaces may significantly alter groundwater recharge processes.

✓ Conclusions

The study has shown that urbanised areas are characterised by a significant alteration of the natural conditions for shallow groundwater recharge. These challenges are particularly acute in areas where groundwater is used for drinking purposes, especially from equipped springs, as is the case in the city of Kharkiv. Based on geospatial analysis of satellite imagery, it was found that impervious surfaces (such as roofs and roads) constitute 29% of private low-rise residential areas and 40% of multi-storey residential areas in Kharkiv. The established ratios of permeable and impervious surfaces enabled the estimation of the degree of anthropogenic transformation of groundwater recharge within the catchment areas of three springs in the city. Specifically, impervious surfaces account for approximately 17% of the catchment area of the Park Yunist Spring. For the Oleksiivske and Hlybokyi Yar springs, these figures are 33.6% and 43.3%, respectively, indicating a significant reduction in natural atmospheric recharge of the aquifer. Continued expansion of impervious surface coverage may lead to an irreversible decline in the discharge of springs, which are actively used by city residents as an alternative source of drinking water.

Measurements of the water flow rates of the studied springs during 2018-2021 confirmed that spring discharge is, to a certain extent, proportional to the size of the catchment area. However, the long-term discharge dynamics

varied considerably: a relatively stable flow from the Hlybokyi Yar Spring (0.8-1.5 L/s); an unstable flow from the Oleksiivske Spring (0.3-1.4 L/s); and a gradual decline in the flow of the Park Yunist Spring (0.5-0.02 L/s). The study demonstrated that in urban environments, the hydrodynamic regime of springs is influenced not only by the ratio of permeable to impervious surfaces in the catchment area, but also by several other critical factors: the technical condition and design of spring capture facilities; the presence of additional recharge from tap water leakage; localised water abstraction at the spring site; and the specific characteristics of the aquifer.

Based on the proportion of impervious surfaces in the springs' catchment areas, it may be concluded that in the urbanised districts of Kharkiv, natural infiltration-based recharge of shallow groundwater has decreased by 17%-43% compared with the natural state, depending on the type of built-up area. Under such conditions, both the qualitative and quantitative characteristics of urban groundwater are affected by the intensity and nature of additional anthropogenic recharge. These findings highlight the necessity of implementing measures to enhance the natural infiltration of precipitation in urban areas. The adverse impact of impervious surfaces on groundwater recharge can be mitigated through the application of nature-based solutions such as permeable road surfaces and green car parks, rainwater harvesting systems, infiltration basins and rain gardens, and green roofs. The applicability and effectiveness of these measures, along with further refinement of the quantitative assessment of infiltration degradation in built-up areas, should be prioritised in future research. Sustainable urban water management, underpinned by nature-based solutions, will strengthen climate resilience and improve water security in urban environments.

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✓ Conflict of Interest

None.

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Оцінка антропогенної трансформації умов живлення підземних вод урбанізованих територій

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✓ **Анотація.** Стратегічним пріоритетом для забезпечення сталого розвитку міських територій в умовах зміни клімату є створення стійких і диверсифікованих систем водопостачання, оскільки змінений міський гідрологічний цикл порушує режим опадів і загальний водний баланс. У цьому контексті джерельні води виступають цінним ресурсом, проте, природне поповнення неглибоких водоносних горизонтів перебуває під загрозою через забудову міських територій, зміни властивостей ґрунту та втрату регулюючих екосистемних послуг. Дослідження було зосереджено на оцінці ступеня антропогенної трансформації умов живлення підземних вод у міських районах Харкова, де налічується близько 30 обладнаних джерел, які активно використовуються населенням для питних цілей. У статті зосереджено увагу на оцінці ступеня антропогенної зміни умов інфільтрації опадів у міській забудові для трьох репрезентативних джерел у Харкові (парк Юність, Олексіївське та Глибокий Яр) із використанням геопросторового аналізу. Було встановлено, що в типових приватних одноповерхових житлових районах непроничні поверхні в середньому становлять до 29 %, тоді як у багатоповерхових житлових забудованих районах вони в середньому досягають 40 % від загальної площі через більшу частку площ, зайняту дорогами та дахами. На основі цих співвідношень було підраховано, що непроничні поверхні займають 17-43 % площі зон живлення досліджуваних джерел. Висновки свідчать про зменшення природного поповнення водоносних горизонтів через перешкоджання інфільтрації на непроничних поверхнях. Шляхом безпосереднього вимірювання дебіту джерел було підтверджено, що на гідродинамічний режим джерел впливає не тільки співвідношення поверхонь, а й технічний стан водозабірних споруд, додаткове живлення від протікання водопровідних мереж та структура водоносних горизонтів. Запропонований методологічний підхід та отримані результати мають важливе практичне значення для органів місцевого самоуправління під час планування та розробки заходів з адаптації міських систем водопостачання в контексті зміни клімату та інших екологічних викликів і загроз

✓ **Ключові слова:** сталий розвиток; міське водокористування; джерела; непроничні поверхні; інфільтрація; геопросторовий аналіз



Geoecological assessment of the state of urban soils and their transformation under the influence of anthropogenic factors

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✓ **Abstract.** Urbanisation and industrialisation are inextricably linked to the transformation of urban soils, posing a significant problem not only at local and regional levels but also globally. The aim of this study was to conduct a comprehensive assessment of the ecological state of soils in urbanised areas under transport and industrial pressure. The study of physicochemical soil properties was carried out using standard methods. Soil buffering capacity was assessed using the method by Professor P. Nadtochij. Key statistical characteristics were calculated, and regression analysis of the study results was performed using Pearson's correlation coefficient. A systematic analysis of the geoecological state of urban soils (urbosols) in the city of Cherkasy revealed that a low humus content (ranging from 0.9% to 7.5%, with an average of 3.0%), soil alkalinisation (pH = 6.5-10.9, with an average pH = 7.9), unfavourable redox conditions (Eh values ranging from 184 to 287 mV, with an average of 239 mV), nutrient imbalance, and a significant content of toxic salts (36% of the studied soils were slightly saline, 23% moderately saline, and 10% highly saline) can have a substantial impact on the stability of the city's urban ecosystems. In terms of acid-base buffering capacity, the soils are in an ecologically stable state. The sum of buffering degrees in both acidic and alkaline ranges exceed 70-75%, with an average equilibrium constant $K = 1.4$. Using the SURFER software package and the Kriging method, spatial interpolation of monitoring data and cartographic zoning of the city territory was carried out based on the main physicochemical soil characteristics. A database and cartographic models of urban soil properties were developed to monitor their spatiotemporal changes, detect critical transformations, and identify zones of ecological and geochemical instability linked to technogenic impact

✓ **Keywords:** physicochemical properties of soils; field research; cartographic modelling; geographic information systems; technogenic impact

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✓ Introduction

In the context of intensive urban development, the ecological state of soils in urbanised areas has become a critical factor for ensuring the sustainable development of regions. Urbanisation is accompanied by significant anthropogenic pressure on the soil cover, leading to contamination with heavy metals, petroleum products, organic compounds, and other toxic substances. Additionally, the consequences of anthropogenic influence on soils include changes in their physical, chemical, and biological properties. Studies conducted between 2020 and 2024 documented the gradual degradation of soil cover caused by excessive anthropogenic pressure. Research by C.S.S. Ferreira *et al.* (2022) and J. Wang *et al.* (2023) identified transportation infrastructure, industrial zones, and landfills as the main sources of pollutants entering the soil. Urbanisation resulted in soil compaction, disruption of drainage properties, and erosion of the topsoil layer. These processes led to a decrease in soil biological activity, contributed to the accumulation of toxins such as heavy metals, and disrupted the nutrient balance. M. Sager (2020) reported that urban soils exhibited increased alkalinity due to construction waste, contained elevated levels of carbon and pollutants, and were characterised by high density and temperature, along with reduced moisture content caused by compaction. The presence of technogenic materials, including construction debris, significantly influenced the migration of water and dissolved substances within the soil profile. Construction activities altered the sequence of soil horizons or mixed the topsoil with underlying layers.

The study by Q. Liu *et al.* (2023) presented the results of mapping heavy metals in soil using various geospatial data, such as remote sensing data, climate, topographic data, and other information on the physicochemical properties of the soil. The authors compared the accuracy of Back-propagation Neural Network (BPNN) and Deep Neural Network (DNN) models for assessing heavy metal content in soil. Based on digital maps reflecting heavy metal content using the DNN model, the study examined the impact of the distance between different spatial scenes on heavy metal contamination in the surrounding soil. The model takes into account all possible combinations of analysed objects, allowing manipulation for decision-making. However, modifying the set of formal concepts may complicate the system's scalability. The work by Ş. Bilaşco *et al.* (2021) presented a methodology based on geographic information system (GIS) spatial analysis for selecting the best hydromelioration solution for the development of a comprehensive gully. The proposed model is developed using spatial databases obtained from unmanned aerial vehicle (UAV) flights, flow velocity modelling, and the creation of three hydraulic analysis models using HEC-RAS software, with the primary goal of evaluating results and databases to identify the best implementation model for stabilising and reducing erosion within the analysed area.

P. Shekar & A. Mathew (2024) explored the use of Revised Universal Soil Loss Equation (RUSLE), RS, and GIS models to assess soil erosion and sedimentation in the

Murradu River Basin. The study utilises GIS for spatial analysis of factors affecting soil erosion, such as climate, topography, vegetation cover, and land use. This allows for the creation of accurate erosion process maps and the prediction of potential sediment yield in various parts of the basin. The RUSLE model is applied to quantitatively assess soil erosion and sediment levels, helping to identify the most vulnerable areas to soil degradation. The results obtained may serve as the foundation for developing effective water resource management strategies and soil restoration measures in the region, promoting sustainable land use and preventing further erosion. V. Melnyk *et al.* (2024) conducted a comprehensive study to assess soil contamination in Rivne, Ukraine, utilising GIS to enhance environmental monitoring. The research focused on the accumulation of heavy metals (HMs) in soils, employing indicators such as the Total Contamination Index (TCI) and Pollution Load Index (PLI) to evaluate contamination levels. The study revealed that 54% of soil samples were "significantly contaminated", while 28% were "moderately contaminated" and 18% showed "no contamination" with HMs. The researchers constructed interpolated surfaces to depict the distribution of total and accumulated HM contamination across the city. This spatial representation allowed for the identification of contamination hotspots, particularly near industrial zones, major highways, and railways. Conversely, areas near water bodies and city outskirts exhibited lower contamination levels.

V. Trigub & S.V. Domuschi (2023) conducted an ecotoxicological study to evaluate the impact of fuel stations on soil contamination with heavy metals in urban areas. The research focused on measuring concentrations of metals such as lead (Pb), cadmium (Cd), and zinc (Zn) in soils adjacent to fuel stations. The study employed various ecological indicators, including the TCI and PLI, to assess the extent of contamination. The study utilised spatial analysis techniques to map the distribution of heavy metal concentrations across the study area. By integrating soil sample data with spatial coordinates, the researchers were able to identify contamination hotspots and assess the spatial variability of pollution levels. This GIS-based approach enabled a more comprehensive understanding of the spatial patterns of soil contamination and facilitated the identification of areas requiring targeted remediation efforts.

In general, approaches to identifying quantitative direct and indirect ecosystem changes in soil under anthropogenic pressure are still limited. Important indicative parameters that characterise both direct and indirect changes in the soil ecosystem include humus content, salinity, redox potential, and the acid-base and buffering properties of the soil cover. When analysing the ecological condition of soils – as with any complex natural process – a systematic approach is required, where processing large volumes of spatially distributed and structured data is essential. In such cases, it is necessary to apply new tools and analytical methods using modern GIS technologies. This study aimed to comprehensively assess the ecological state of urban soils

by examining their physicochemical properties, evaluating anthropogenic impacts, and identifying environmental risks to urban ecosystems.

✓ Materials and Methods

The approach presented in this work includes the following stages: soil survey using standard methods; mapping of soil properties; and assessment of overall soil quality in terms of ecosystem service provision. Using the SURFER geographic information software package, the obtained data were extrapolated across the entire urban area and zoned according to key physicochemical indicators (humus content in soil, pH-water indicator, acid-base buffering capacity, content of exchangeable calcium and magnesium ammonium content) for visualisation purposes. Research sites were selected within various functional zones of the city of Cherkasy (Fig. 1). The geographical reference of the test points was carried out using a GPS navigation system. The selection of study plots was based on an analysis of natural and anthropogenic factors influencing the formation of urban landscapes in areas of permanent emissions, taking into account the indicator of cumulative environmental load (Myslyuk *et al.*, 2019). Considering that most soil-based ecosystem services in urban areas are provided by green spaces – particularly oxygen production – soil assessment and the evaluation of its related functionality were focused on the study of soils in roadside green belts.

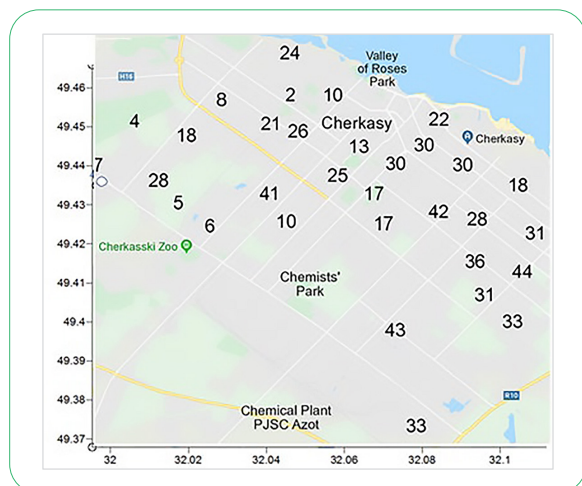


Figure 1. Map of the location of the research sites

Source: compiled by the authors

The primary objective of the field-based ecological investigations was the development of GIS-based maps and the assessment of soil disturbance through analytical and observational methods, aimed at generating spatial distributions of soil contamination. Soil samples were collected following an envelope sampling design within 5×5 m plots and subsequently composited into a single representative sample. In undisturbed (natural) soil conditions, sampling was conducted at a depth of 10–20 cm, whereas in anthropogenically modified soils – where intact soil layers were absent – samples were obtained from a depth of 20–30 cm. Prior to analysis, coarse fragments, above-ground biomass, and root

material were manually removed. Each composite soil sample had a mass of approximately 1.5 kg. Sampling was performed using a soil auger equipped with a 50 mm diameter metal coring cup. Site selection was guided by landscape, geomorphological, and pedological maps to ensure representation across all zonal soil types within a structured sampling grid. In total, 47 soil samples were collected across geoecological monitoring plots. Analyses of the samples were carried out in the universal laboratory of Cherkasy state technological university at the Department of Ecology. Sampling of soil and plant material and their subsequent research was carried out in accordance with current regulations. Soil samples were taken from experimental plots in accordance with methodological recommendations and the State Standard of Ukraine: DSTU 4287:2004 (2004), DSTU ISO 10381-5:2009 (2009), DSTU ISO 10381-4:2005 (2009), DSTU GOST 17.4.4.02:2019 (2019).

The basic physical and chemical properties were determined for the studied soil samples. The content of mobile potassium compounds was determined by the Chirykov modification method in accordance with DSTU 4115:2002 (2002). The content of total humus was determined by the Tyurin method in the CINAO modification according to DSTU 4289:2004 (2005). The content of exchangeable calcium and magnesium – according to DSTU 7861:2015 (2015) in the modification of the Sokolovsky NNC IGA, pH-water indicator – according to DSTU 8346:2015 (2015). Ammonia content in soils was determined in accordance with DSTU 4725:2007 (2007). Soil buffering capacity was assessed using the method developed by Professor P.P. Nadtochiy *et al.* (2010), which is based on potentiometric determination of pH shifts in a soil suspension depending on changes in acid (HCl) and alkali (NaOH) concentration, following the standard water-to-soil ratio of 2.5:1 recommended by the Third International Congress of Soil Science (1935). For the studied parameters, the main statistical characteristics were calculated and regression analysis was performed using the Pearson correlation coefficient. Based on the obtained analysis results, databases were created in Microsoft Excel and then in MapInfo Professional, which are needed for the interpolation of ecological maps in Surfer. Mapping of the city area to identify spatial patterns in the formation of risk zones was carried out using Golden Software Surfer.

✓ Results

The territory of the city of Cherkasy is entirely situated within the forest-steppe zone. According to its geomorphological and orohydrographic characteristics, the natural soil cover of the area is heterogeneous. The landscapes of Cherkasy are primarily formed by loess and loess-like loams, as well as sandy loams of various origins. The soil cover is non-uniform, characterised by a light mechanical composition and the presence of anthropogenic inclusions (e.g., fragments of construction debris and allochthonous materials). The soils are contaminated with xenobiotics, particularly heavy metals (Yehorova *et al.*, 2024). Humus is a critical factor in the resilience of soils to persistent anthropogenic pressures. It contributes

to soil structuring, optimises physical properties, enhances absorption capacity and buffering ability, and facilitates the accumulation of biophilic chemical elements and energy.

Studies have shown that the soils of Cherkasy are predominantly low in humus content (Fig. 2). Humus levels range from 0.9% to 7.5%, with an average value of 3.0%, a standard deviation of 1.5, a dispersion of 2.3, and a coefficient of variation of 50%. Such low values can be explained by ongoing soil contamination and the degradation of the fertile topsoil layer. Additionally, a significant amount of sand is applied to roads during winter, and the process of humus formation is virtually absent due to the systematic removal of fallen leaves, small branches, and fruits. As a result, organic matter is not replenished, and the decomposition, humification, and mineralisation of the remaining plant residues are inhibited by the cumulative effects of anthropogenic pressures. Low levels of organic matter create unfavourable conditions for plant growth and reduce the soil's capacity to adsorb heavy metals, posing a potential threat to both the urban ecosystem and the health of the city's population.

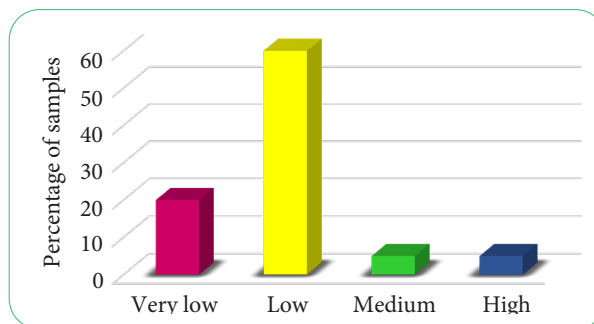


Figure 2. Humus content in soil

Source: compiled by the authors

Using the geo-information software package SURFER for data visualisation, an extrapolation of the obtained data was performed for the entire city area, followed by zoning based on humus content (Fig. 3). The modelling results revealed a significant level of and contrast in technogenic anomalies within the city's soil cover.

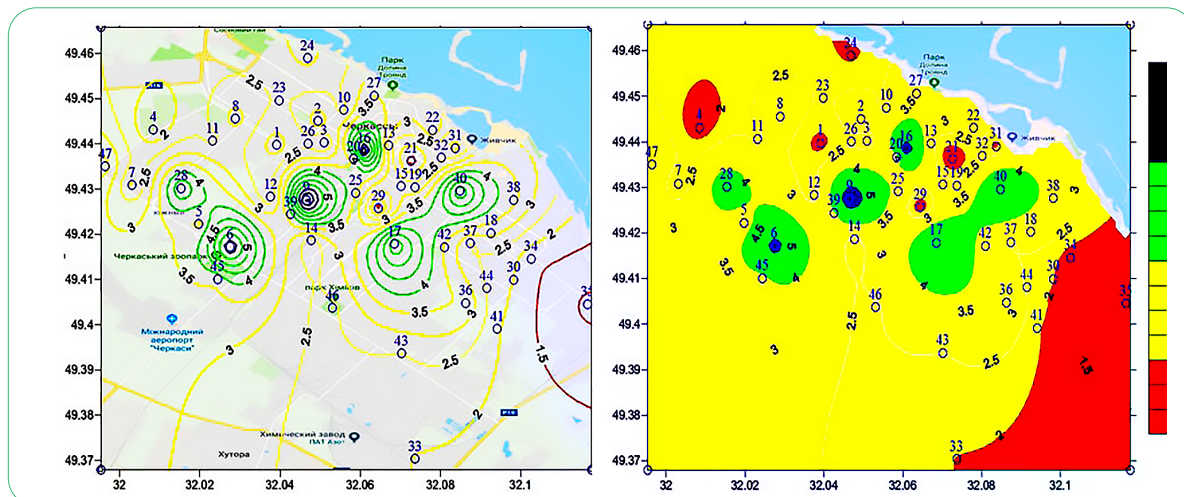


Figure 3. Zoning of Cherkasy City area based on humus content

Source: compiled by the authors

The determination of soil pH and the identification of its sources are essential for the restoration of soil fertility. Additionally, the mobility and bioavailability of heavy metals decrease with increasing pH levels. Soil acidity influences the transport of metals and plays an important role in plant development processes (Msimbira & Smith, 2020). The current soil acidity in Cherkasy ranges from 6.5 to 10.9, with an average value of 7.9, a standard deviation of 0.7, and a variance of 0.5. The studied soils, in terms of pH, are characterised as homogeneous (with a coefficient of variation of 9%), predominantly alkaline (Fig. 4), which does not support the ecosystem service of providing plants with necessary macro- and micronutrients. Soil alkalisation in Cherkasy is likely caused by the application of sand-salt mixtures during winter to combat ice, the deposition of carbonate dust, ash, bicarbonate atmospheric precipitation, the dissolution of carbonate technogenic inclusions from

construction debris in the soil, and emissions from industrial enterprises, all of which gradually enter the soil over time (Shokri *et al.*, 2024).

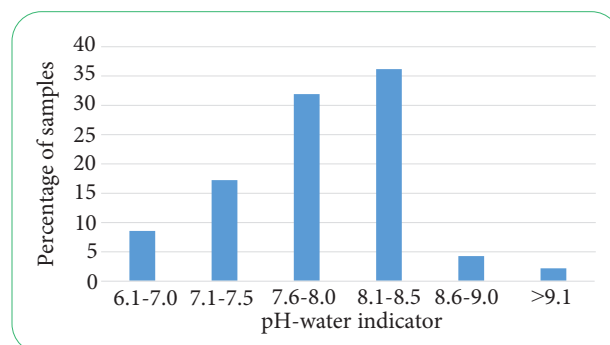


Figure 4. Distribution of soils by current acidity

Source: compiled by the authors

The conditions for plant nutrition with necessary macro- and micronutrients are suboptimal due to the current acidity levels, which can lead to the deterioration of green spaces and the failure of these spaces to perform their functions. The main centres of soil alkalisation in urban areas are concentrated in the industrial zones

of the city and along the roads of the residential areas (Fig. 5). It should be noted that in the areas of soil alkalisation, an alkaline geochemical barrier forms, which promotes the surface accumulation of chemical elements and slows down the vertical and horizontal migration of heavy metals.

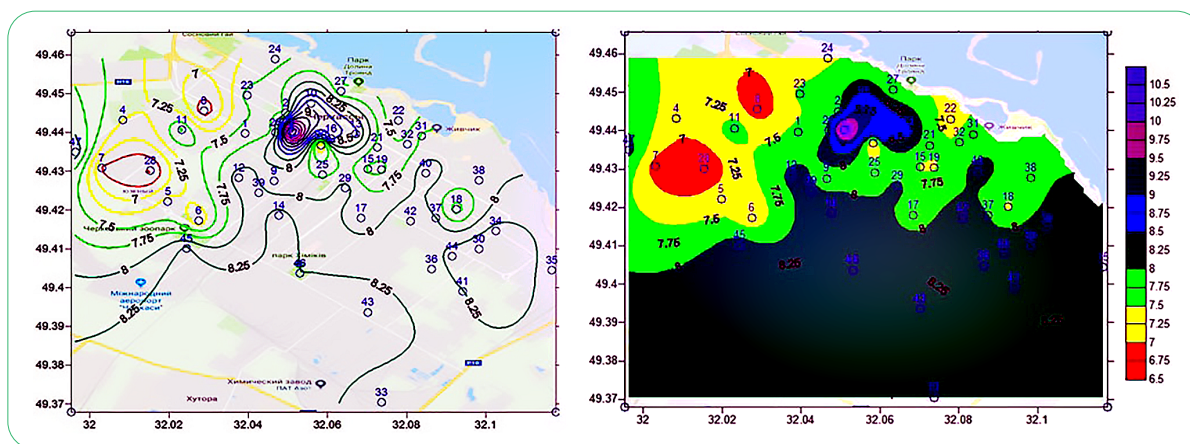


Figure 5. Zoning of Cherkasy City area based pH-water indicator

Source: compiled by the authors

According to pH values, 63% of the studied soils are only partially capable of performing the sorption function (protecting groundwater from pathogenic microorganisms), while 44% perform the sanitary function (protecting groundwater from pollutants). Many redox reactions in soils are mediated by hydrogen ions, so the redox state of soils, which is influenced by pH levels, affects soil formation processes by regulating the decomposition of organic residues, the accumulation rate, and the nature of humus substances, as well as the mobility and biological availability of nutrients (nitrogen and phosphorus compounds, microelements) in the soil-plant system. Redox conditions significantly alter the processes of soil microorganism activity, especially nitrogen-transforming microorganisms. For example, nitrogen-fixing bacteria cease growth when the Eh value exceeds 500 mV (Dayo-Olagbende *et al.*, 2020); optimal redox conditions for nitrification range from 350 to 500 mV, while denitrification occurs under conditions of less than 350 mV. The redox potential (Eh) is an integral indicator for assessing the stability of redox processes in soils, which affect its ecological properties (i.e., the ability to maintain ecological balance) in the soil-atmosphere and soil-plant systems.

The redox potential (Eh) of soils in the studied areas ranges from 184 to 287 mV, with an average value of 239 mV (standard deviation 32.9, coefficient of variation 14%). At these Eh values and $\text{pH} \geq 8.0$, denitrification processes will predominate in the soil, and plants may experience a deficiency of Fe and Mn. In areas with $\text{Eh} < 200$ mV, the development of reduction processes is likely (Olivier *et al.*, 2021). The low redox potential of Cherkasy City soils may be due to poor soil aeration caused by compaction, moisture regime, organic matter content, and microbial activity. Graphical models of pH-buffering capacity provide

a more objective assessment of the acid-base properties of soils. The buffering capacity of the studied soils in Cherkasy ranged from low to very high in the acidic range and from moderate to high in the alkaline range (Fig. 6).

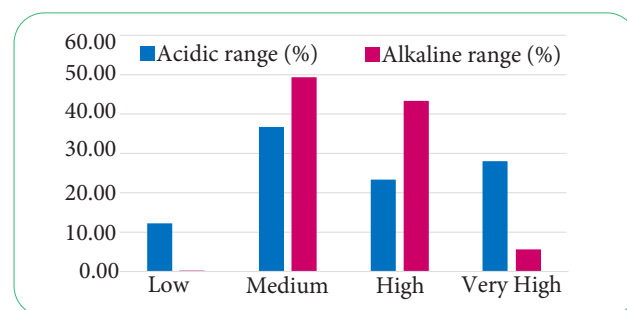


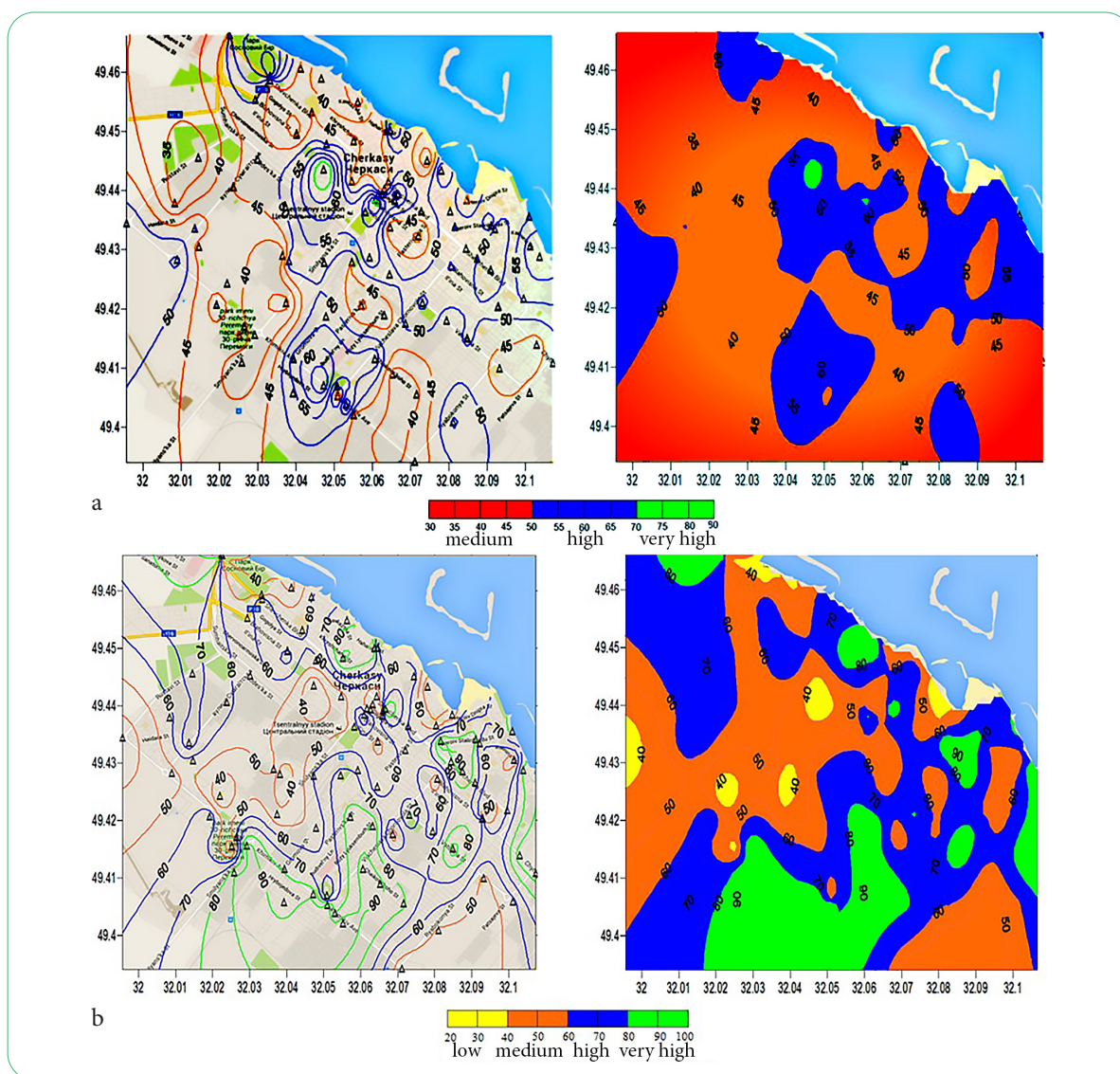
Figure 6. Soil ranking by acid-base buffering capacity

Source: compiled by the authors

A very high degree of acid-base buffering capacity in soils with respect to the action of acidifying substances is characteristic of areas located within the influence zones of such powerful sources of landscape pollution in the city as the PrAT "Azot", PrAT "Cherkaske Khimvolokno" VP "Cherkaska TPP" and road transport. The research results showed that the soil ecosystems of Cherkasy function predominantly in a relatively ecologically stable mode based on acid-base buffering capacity indicators, with ecological imbalance observed only in certain areas. The equilibrium constant ranged from 0.3 to 2.7, with an average value of 1.4. Fifty-eight percent of the samples had better buffering properties in the acidic range than in the alkaline range, 20% in the alkaline range, and 22% of the samples had almost identical buffering properties against both acids and alkalis.

The sum of the buffering degrees of the acidic and alkaline ranges varied from 61% to 162%, with an average value of 113%. Soil ecosystems function in a relatively ecologically stable mode when the sum of the buffering degrees of the acidic and alkaline ranges exceeds 70-75%, and the equilibrium constant ranges from 0.6 to 4.0. Moreover, the closer this value is to 1, that is, the more symmetrical the buffering curves are in the acidic and alkaline ranges, the better the buffering mechanisms of the soil function, and the more stable the functioning of this ecosystem. The prevailing asymmetry of the buffering zones is due to the physicochemical properties of the soil. As is known, carbonate soils, due to their saturation with calcium and magnesium,

possess buffering mechanisms with a pronounced asymmetric function, which is reflected in the predominance of proton (H^+) neutralisation processes. That is, these soils exhibit a significant acid-neutralising capacity. A comparative analysis of the soil's buffering properties in the acidic and alkaline ranges (Fig. 7) revealed considerable variation across the city in terms of the acid-base buffering capacity in the acidic range, which is likely due to its technogenic decalcification resulting from prolonged and intensive inputs of acidifying agents from the CHP. The correlation coefficient between the sum of absorbed bases and the degree of acid-base buffering capacity of the soils in Cherkasy in the acidic range is 0.53.



under the influence of a complex combination of natural self-organisation processes and various urbanogenic activities. Analysis of toxic salt content showed that almost 30% of the studied soils are non-saline, 36% are weakly saline, 23% are moderately saline, and 10% have a high salinity level (Fig. 8). It is known that even in weakly saline soils, growth inhibition is observed in 25% of woody vegetation (El Sabagh *et al.*, 2021). Statistical analysis of data using

Pearson's correlation coefficient indicates that chloride ions (R^2 ranging from 0.53 to 0.85, with an average value of 0.67) and bicarbonate ions (R^2 ranging from 0.19 to 0.82, with an average value of 0.59) contribute most to the overall soil salinity. This is explained by their high concentration among leached ions and the high ionic conductivity of chloride ions. The main centres of soil salinisation are concentrated along the roads of the city's residential zones.

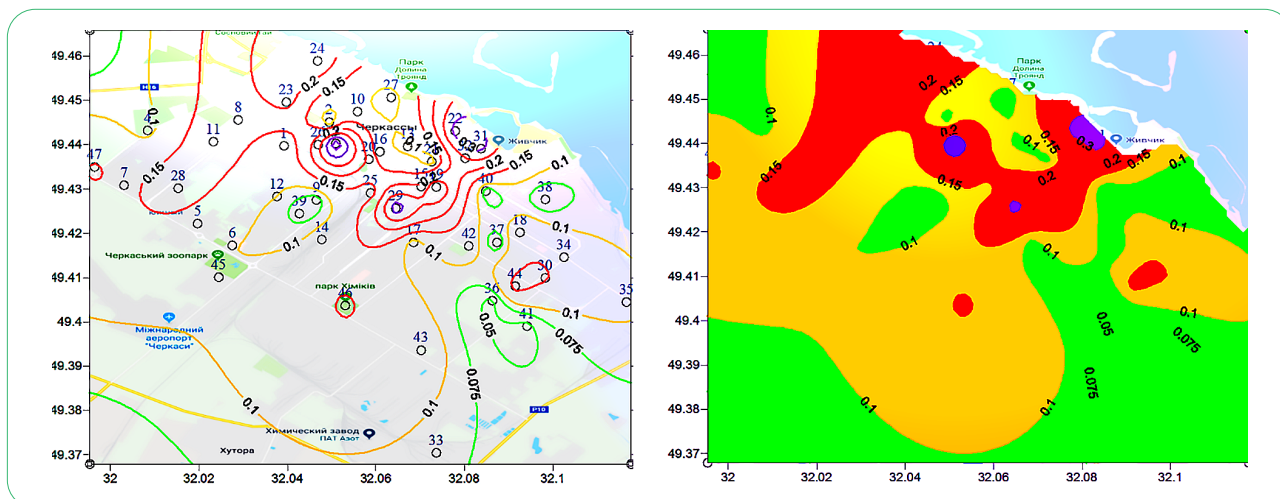


Figure 8. Zoning maps of Cherkasy urban soils based on the total toxic salts content

Source: compiled by the authors

Calcium plays an important role in soil formation processes. It is part of the soil adsorption complex (SAC), participates in exchange reactions of the soil solution, and determines the high buffering capacity of the soil in the acidic range of the environment (Jing *et al.*, 2024). The best conditions for plant nutrition are created when Ca^{2+} ions predominating in the SAC. Partial replacement of Ca^{2+} by Mg^{2+} in the SAC leads to deterioration of the soil's water-physical properties and the quality of humus, which results in reduced soil fertility. Calcium deficiency primarily affects the plant root system. Additionally, Ca^{2+} ions play an important role in altering the direction of metabolic processes in plants under stress conditions. Mg^{2+} ions are also crucial for

plant growth and development, just like Ca^{2+} . At the same time, high concentrations of Mg^{2+} can negatively affect the water-stability of soil aggregates, limit the uptake of Mn by plants, and its deficiency leads to chlorosis and necrosis of leaves and stems (Ishfaq *et al.*, 2022). The conducted studies showed that the content of Ca^{2+} in the SAC varied from 1.90 to 7.25 mmol/100 g of soil with an average value of 3.60, a standard deviation of 1.18, a variance of 1.38, and a variation coefficient of 33%. The content of Mg^{2+} varied from 0.00 to 6.00 mmol/100 g of soil with an average value of 1.96 (standard deviation of 1.65, variance of 2.72, variation coefficient of 80%). For many of the studied soil samples, the content of Mg^{2+} was significantly higher than that of Ca^{2+} (Fig. 9).

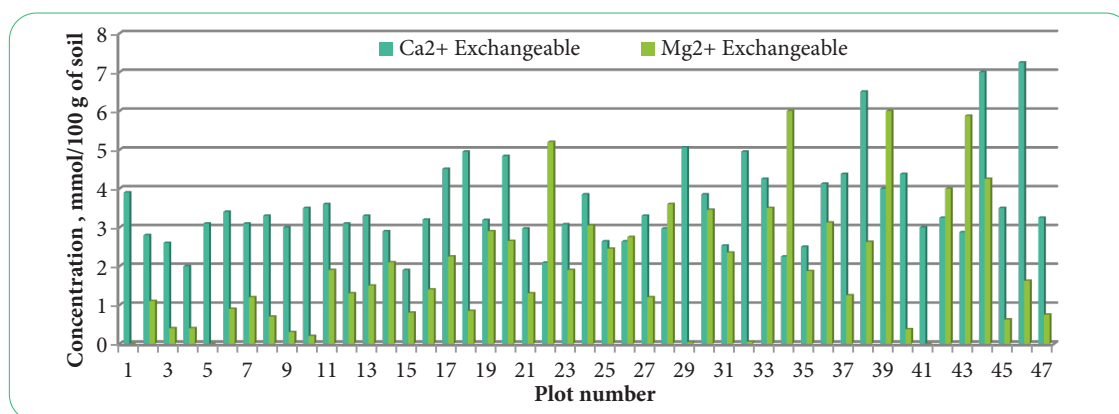


Figure 9. The content of exchangeable Calcium and Magnesium in the soils of the city

Source: compiled by the authors

A significant heterogeneity of the studied soils in terms of Mg^{2+} content was characteristic (variation coefficient of 84%), which is likely due to the use of magnesium chloride and sodium chloride mixtures in winter to combat icing, as well as the leaching of these ions from the SAC during hydrogen ion neutralisation processes. Soil classification based on the content of exchangeable calcium (Ca^{2+}) and magnesium (Mg^{2+}) revealed that a very low Mg^{2+} content was observed in 13% of the analysed soil samples. Low levels of both Ca^{2+} and Mg^{2+} were found in 11% of the samples. A medium content was recorded in 81% of samples for Ca^{2+} and in 13% for Mg^{2+} . Elevated levels were detected in 9% of samples for Ca^{2+} and in 15% for Mg^{2+} . High Mg^{2+} content was observed in 9% of the samples, while a very high content was found in 40% of the samples (Fig. 10).

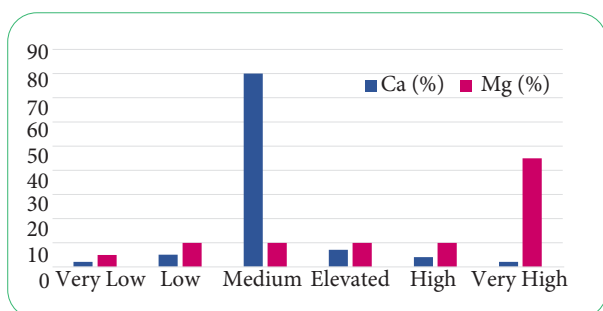


Figure 10. Grouping of soils

by exchangeable Calcium and Magnesium content

Source: compiled by the authors

According to the results of soil studies conducted in the city of Cherkasy, the calcium-to-magnesium cation ratio is not optimal. In the composition of exchangeable cations in typical chernozems and meadow-chernozem soils of the forest-steppe zone, exchangeable calcium predominates. As a rule, the cation exchange capacity (CEC) is 70-85% saturated with Ca^{2+} , and only in solonchak-like soils is an increased content of exchangeable Mg^{2+} observed (Chaganti *et al.*, 2017). The CEC of an ideal soil should contain approximately 65% calcium and 10% magnesium. According to the results of soil studies conducted in the city of Cherkasy, the calcium-to-magnesium cation ratio is not optimal.

Potassium is classified as an essential macronutrient required for plant development, being one of the three primary

nutrients needed in the largest quantities. (Hasanuzzaman *et al.*, 2018). In terms of K^{+} content, the soils of Cherkasy exhibit considerable heterogeneity; however, they are generally well-supplied with this important plant nutrient. The K^{+} content ranges from 0.12 to 6.20 mmol/100 g of soil, with an average value of 0.59 mmol/100 g, a standard deviation of 0.67, a variance of 1.39, and a coefficient of variation of 95%. The heterogeneity in potassium content among the studied soils can be attributed to differences in the vegetation cover of the model plots. With regard to water-soluble potassium, 89% of the studied soils are poorly supplied (<10 mg/kg), 4% are moderately supplied (10-30 mg/kg), and 7% are well supplied (>30 mg/kg) with this essential plant nutrient (Fig. 11).

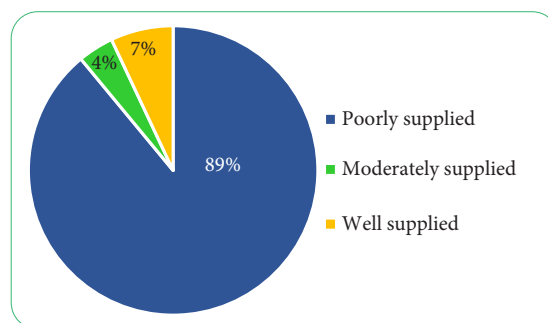


Figure 11. Grouping of soils

by water-soluble potassium content

Source: compiled by the authors

Mineral nitrogen compounds are also essential for plant nutrition. The directly available forms of nitrogen for plants include ammonia (in the form of ammonium ions) and nitrates. Ammonium ions are present in soils as water-soluble salts of exchangeable and fixed (non-exchangeable) ammonium. The formation and accumulation of mineral nitrogen in the soil depends on many factors, but primarily on the quantity and quality of organic matter. The alkaline reaction of the soil increases the ability to fix ammonium ions in the CEC. The ammonium content in the soils of Cherkasy ranges from 0.000 to 0.014 (Fig. 12), with an average value of 0.003 mmol/100 g of soil (coefficient of variation – 1.01, standard deviation – 0.14, variance – 0.02). This variation can be explained by both the absorption of ammonium by plants and microorganisms and the low humus content and soil alkalisation, which is typical for urban soils in the city.

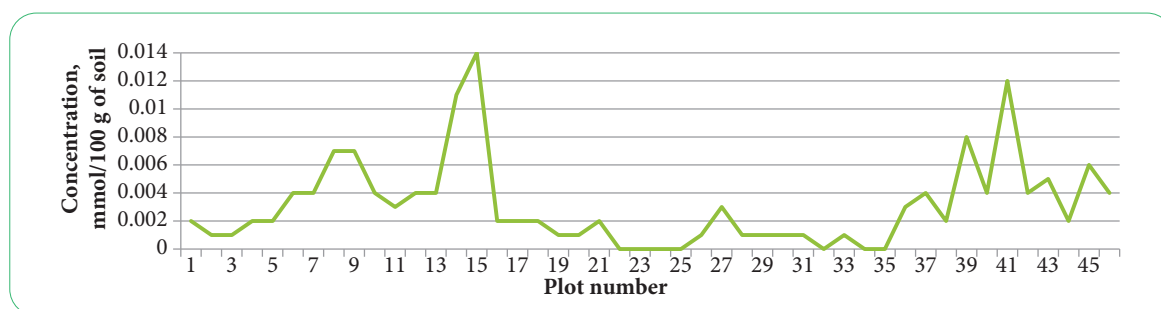


Figure 12. Exchangeable Ammonium content in Cherkasy City soils

Source: compiled by the authors

One of the primary reasons for the elevated levels of ammonium content is the specific nature of the urban soils in Cherkasy, which are characterised by low humus content and an alkaline reaction – factors that facilitate the fixation of ammonium ions within the soil complex. The alkaline nature of the city's soils enhances the ability to retain ammonium in its non-exchangeable (fixed) form, thereby reducing its availability to plants. Additionally, the formation and accumulation of mineral nitrogen in the soil is influenced by both the quantity and quality of organic matter, which is limited in urban soils due to the processes of urbanisation. In general, the low ammonium content in the soils of Cherkasy may suggest insufficient availability of this element to plants, potentially affecting the growth and development of vegetation within the city. This underscores the importance of improving soil composition – specifically by increasing humus content and managing soil pH – in order to support fertility in urbanised environments.

✓ Discussion

In the context of environmental monitoring of urban areas and geochemical mapping analysis, it is important to highlight the valuable input of several recent studies that focus on key methodologies used in geochemical mapping. The study by J. Wang *et al.* (2024) introduced a novel approach to geochemical mapping by addressing the uncertainties inherent in defining elemental associations related to mineralisation. This methodology involves clustering the study area based on elemental similarities, identifying elemental associations within each cluster, and detecting geochemical anomalies indicative of underlying geological processes. The approach was applied to stream sediment geochemical samples from north-western Sichuan Province, China, revealing two distinct clusters corresponding to Paleozoic and Triassic lithological units. The findings suggest that the region holds significant potential for discovering gold deposits, particularly near known mineralisation sites.

From a GIS perspective, this study underscored the importance of spatial analysis in geochemical mapping. By integrating elemental data with spatial clustering techniques, the researchers were able to delineate areas with distinct geochemical signatures, enhancing the accuracy of anomaly detection. GIS tools facilitate the visualisation and interpretation of complex geochemical data, allowing for the identification of spatial patterns and relationships that might be overlooked in traditional analyses. Moreover, the incorporation of uncertainty quantification into the mapping process adds a layer of robustness, enabling more reliable decision-making in mineral exploration.

The study by F. Parsaie *et al.* (2021) focused on digital modelling and mapping the spatial distribution of topsoil total nitrogen (TN) in the Qorveh-Dehgolan plain, an area of 150,000 hectares, using machine learning algorithms. The authors applied Random Forest (RF), Decision Tree (DT), and Cubist (CB) models to predict TN

concentrations based on a range of environmental covariates. These included geomorphometric attributes from a digital elevation model, spectral indices from SENTINEL-2 satellite data, soil properties, and spatial variables like latitude and longitude. The Boruta algorithm was used to select the most relevant covariates, which led to the identification of 14 key factors influencing TN distribution. Validation of the models revealed that RF provided the most accurate predictions, with the lowest root mean square error (RMSE) and mean absolute error (MAE). The study also generated uncertainty maps, highlighting areas with high prediction reliability. The findings emphasise the importance of geomorphometric variables and remote sensing indices, such as SAVI and NDVI, in soil nitrogen modelling. This research offers a robust methodology for mapping soil nutrients, supporting sustainable land management practices and precision agriculture.

T. Shi *et al.* (2021) investigated the growing issue of lead (Pb) contamination in urban topsoil, which is exacerbated by rapid urbanisation in China. The study focused on developing spatial models to map Pb concentrations in urban soils using a combination of proximal and remote sensing data. Proximal sensing reflectance spectra, along with vegetation and land-use factors derived from Landsat images, were used as landscape variables to predict Pb levels. The authors employed two hybrid statistical approaches, regression kriging (RK) and geographically weighted regression (GWR), to establish prediction models. The results showed that the use of combined proximal and remote sensing data significantly improved the accuracy of Pb concentration predictions compared to using either data source individually. Among the two methods, GWR demonstrated superior performance. This study underscored the effectiveness of using joint proximal and remote sensing data for mapping urban soil contamination, offering a timely and accessible tool for environmental monitoring.

The P. Khosravani *et al.* (2023) explored the digital mapping and spatial modelling of soil physical and mechanical (SPM) properties in the semi-arid region of Marvdasht Plain in Fars Province, Iran. This study was aimed to predict key soil properties, including mean weight diameter (MWD), geometric mean diameter (GMD), shear strength (SS), and penetration resistance (PR), using machine learning algorithms such as random forest, Cubist, and k-nearest neighbour. A total of 200 field observations were made to collect data from topsoil and subsoil, with additional environmental factors derived from topographic and remote sensing data. Two different covariate scenarios were tested, combining soil properties and environmental factors. The results revealed that soil variables, particularly clay content and soil organic matter (SOM), significantly influenced the prediction of SPM properties, with the k-nearest neighbour algorithm performing well in predicting SPM properties, and random forest providing the highest accuracy for penetration resistance at the 15–30 cm depth.

The authors G. Meza Mori *et al.* (2022) applied the MEDALUS model to assess soil degradation risks in the

Amazon region using GIS. The model takes into account factors such as climate, soil types, vegetation cover, and land use intensity, allowing for the creation of maps of ecologically sensitive areas. This enables the identification of zones requiring ecological restoration and contributes to more accurate forecasting of degradation processes. The authors emphasise the importance of a comprehensive approach to soil degradation, as it results from the interaction of various natural and anthropogenic factors. The study provides recommendations for sustainable land management in the Amazon, focusing on strategies to conserve natural resources and support local communities.

The study conducted by S. Bangroo *et al.* (2023) presented the results of spatial distribution of soil properties using both universal and ordinary kriging methods. Spatial assessment and mapping of key physicochemical soil indicators (pH, electrical conductivity, organic carbon, nitrogen, phosphorus, and potassium) were carried out using hybrid geostatistical models. However, existing environmental variables that assist in the spatial assessment and mapping of soil components face a key issue – it is difficult to obtain ecological variables with high correlation, which leads to low accuracy in the predicted models.

The author M.A.E. AbdelRahman (2023) examined global issues of land degradation and desertification, which pose serious threats to food security, livelihoods sustainability, and biodiversity. The use of GIS and remote sensing for monitoring and mapping land degradation allows for effective assessment of soil and water resources. The authors highlight the importance of applying technologies to analyse processes such as erosion, soil salinisation, and fertility decline, as well as to identify areas that require restoration. The authors also emphasise the need for the development of global initiatives to raise awareness about the economic consequences of degradation and promote sustainable land resource management.

The publication by B. Pradeep Kumar *et al.* (2022) addressed the geo-environmental monitoring and assessment of land degradation and desertification in semi-arid regions using satellite data and environmental indices. The study employs Landsat 8 OLI/TIRS imagery, along with Land Surface Temperature (LST) and Normalised Difference Vegetation Index (NDVI), to assess the extent and dynamics of land degradation in a semi-arid region. The authors integrate these remote sensing data to develop a comprehensive approach for monitoring land degradation processes, focusing on their impact on vegetation health, soil moisture, and overall land productivity. The findings indicate that LST and NDVI are effective in tracking desertification and land degradation over time, and the study provides a framework for using satellite-based data in environmental management. The results highlight the potential of remote sensing technologies for assessing environmental challenges in semi-arid regions and offer valuable insights for land conservation and sustainable development practices.

The integration of GIS and Earth remote sensing technologies provides a comprehensive toolkit for addressing a

wide range of environmental monitoring challenges. This highlights the significance of developing and applying new technologies in ecology as a crucial step toward achieving sustainable development. Given the growing importance of this issue, the article explores the potential of GIS for local-level environmental monitoring, with a specific focus on assessing the state of soil cover in the Cherkasy Region. The authors evaluate various monitoring approaches, including both remote sensing and chemical methods, and suggest strategies for creating an environmental monitoring system utilising GIS technologies.

✔ Conclusions

Based on the results of the conducted study, a comprehensive assessment of the geoecological state of the urban soils in Cherkasy has been provided. Analysis of 47 soil samples from different functional zones of the city revealed significant spatial heterogeneity of urban soils. The main issue is the low humus content (ranging from 0.9% to 7.5%, with an average of 3.0%) and alkalinity (pH = 6.5–10.9). The redox potential (Eh) of soils varies between 184 and 287 mV, with an average of 239 mV, which promotes denitrification.

According to the content of toxic salts, only 30% of the studied soils are non-saline, 36% are slightly saline, 23% are moderately saline, and 10% have a high level of salinity. A high content of exchangeable Mg^{2+} compared to Ca^{2+} may significantly affect the development of green spaces and the ecological functions of the soil. Analysis of graphical models of soil pH-buffering capacity indicates their environmentally stable condition. The total buffering capacity in both acidic and alkaline ranges exceed 70–75%, with an average equilibrium constant $K = 1.4$. The imbalance of nutrients in the soil, low humus content, and alkaline environment can significantly affect the development of urban greenery and the soil's ability to adsorb heavy metals.

The conducted research opens new possibilities for creating and implementing an effective monitoring system using a systemic approach and modern GIS technologies. The development of a database and cartographic models of the geoecological condition of urban soils will enable tracking their transformation over time and space. This will allow for the identification of early stages of significant changes and the determination of risk zones for the development of hazardous exogenous processes and unstable ecosystems, thereby contributing to the development of effective environmental protection measures.

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Геоєкологічна оцінка стану урбоземів та їх трансформація під впливом антропогенних чинників

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✓ **Анотація.** Урбанізація та індустріалізація нерозривно пов'язані з трансформацією міських ґрунтів, що становить значний виклик не тільки на місцевому та регіональному рівнях, але й у глобальному масштабі. Метою роботи була комплексна оцінка екологічного стану ґрунтів урбанізованих територій в умовах транспортного та промислового навантаження. Дослідження фізико-хімічних властивостей ґрунтів проводилися за стандартними методиками. Буферність ґрунтів оцінювали за методикою П. Надточого. Розраховані основні статистичні характеристики та проведено регресійний аналіз результатів дослідження з використанням коефіцієнта кореляції Пірсона. Системний аналіз геоєкологічного стану урбоґрунтів (урбозолів) міста Черкаси показав, що для них характерним є низький вміст гумусу (від 0,9 % до 7,5 %, при середньому значенні 3,0 %), підлуження ґрунтів ($pH = 6,5-10,9$, при середньому значенні $pH = 7,9$), несприятливі окислювально-відновні умови (значення Eh від 184 до 287 мВ, при середньому 239 мВ), незбалансованість поживних елементів та значний вміст токсичних солей (36 % досліджених ґрунтів є слабозасоленими, 23 % – помірнозасоленими та 10 % – високого рівня засоленості) можуть чинити істотний вплив на стійкість урбоєкосистем міста. За кислотно-основною буферністю ґрунти перебувають в екологічно стабільному стані. Сума ступенів буферності як в кислому, так і в лужному діапазонах перевищує 70-75 %, при середній константі рівноваги $K = 1,4$. За допомогою програмного комплексу SURFER та методу Крігінга проведено просторову інтерполяцію даних моніторингу та картографічне зонування території міста за основними фізико-хімічними характеристиками ґрунтів. Створено базу даних та картографічні моделі властивостей ґрунтів міста для моніторингу їх просторово-часових змін, виявлення критичних трансформацій та визначення зон еколого-геохімічної нестабільності, пов'язаних із техногенним впливом

✓ **Ключові слова:** фізико-хімічні властивості ґрунтів; польові дослідження; картографічне моделювання; геоінформаційні системи; техногенний вплив



Modern methods of monitoring estuarine waters on the example of the Tiligul Estuary

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✓ **Abstract.** Manual monitoring of the eutrophication status of water bodies such as estuaries is a rather difficult task. Drone technology can be used to assist in monitoring any water body. This study was conducted with the aim of applying remote sensing methods based on unmanned aerial vehicles (UAVs) to obtain eutrophication indicators in the waters of the Tiligul Estuary. The information was based on data collected by drones on the level of eutrophication and the state of marine areas. A DJI Phantom 4 Pro drone was used to collect data from the air. Four sampling points were selected for testing, where the normalised vegetation difference index and normalised turbidity difference index were evaluated. Exsitu data, such as nitrate concentration and phosphate concentration, were also obtained. A trophic status index was calculated to describe the algae content in the estuary. The UAV hyperspectral images were orthorectified and georeferenced in Agisoft PhotoScan software and the normalised difference vegetation index values were evaluated in ArcGIS. The results showed a correlation between the vegetation difference index values and the concentration of nitrogen and phosphorus with coefficients of 0.7079 for phosphorus concentration and 0.7004 for nitrogen concentration, respectively. This study confirmed the applicability of remote sensing for water resource management using UAVs, which is characterised as a fast and simple methodology. A qualitative assessment and control of environmental parameters during the solution of environmental monitoring tasks for marine areas and coastlines was proposed. It was noted that mathematical and simulation modelling methods contribute to the formation of functional and information models, and system analysis methods are also used to identify structural relationships between components of complex systems. The results of the study will enable the further use of UAVs and other remote sensing methods for monitoring and forecasting the state of estuaries and marine areas

✓ **Keywords:** marine environment monitoring; unmanned aerial vehicles; estuary; coastal zone management; eutrophication

✓ Introduction

Preserving the ecological safety of marine areas and coastal zones is important for countries with access to the sea. In the context of increasing anthropogenic pressure on marine ecosystems, global climate change and growing transport traffic,

it is extremely important to continuously monitor the state of water resources and coastal ecosystems. Timely detection of environmental threats and man-made accidents (oil spills, chemical pollution, changes in water temperature and

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salinity, erosion processes) makes it possible to minimise damage and mitigate the consequences. In this context, modern mobile monitoring information systems are of particular importance. Mobile monitoring platforms – such as unmanned aerial vehicles (drones), automated marine buoys and specialised boats with sensors – enable field research, which is particularly important for regions with hard-to-reach coastal areas. The use of mobile information systems facilitates more accurate tracking of environmental parameters, monitoring of biodiversity, prevention of natural disasters (such as storm surges and floods) and control over compliance with international environmental standards.

The development of information systems for monitoring marine and coastal areas is being actively studied in scientific circles. Scientists analyse technical solutions, improve data collection methods and develop algorithms for the rapid detection of environmental threats. Various methodologies, mechanisms, principles and approaches have been developed to assess the state of the environment during environmental monitoring using aerospace technologies. An analysis of the experience of scientists H. Zhang *et al.* (2022), who studied aquatic ecosystems, has shown that their protection and rehabilitation is only possible with the active use of relevant information technologies in the management of water bodies.

As noted in the work of I. Afán *et al.* (2022), being fundamental to global biodiversity and critical to human well-being, aquatic ecosystems are characterised by their profound diversity, which is due to a multitude of environmental conditions and complex population structures. This inherent complexity requires nuanced monitoring to ensure conservation, protection and restoration. However, existing monitoring methods face significant challenges in capturing the full extent of this complexity, which hinders effective ecosystem management. Traditional methods, including remote sensing using satellites and on-site measurements, have provided valuable information, but advances in computer IT technologies in the information age are

prompting change. According to researchers O. Trofymchuk *et al.* (2014), global threats such as biological invasions, climate change, intensified land use and water depletion further emphasise the urgency.

These challenges highlight the need for more modern monitoring approaches that can provide high-resolution data in real time at different spatial scales. Given these challenges and achievements, an integrated approach incorporating state-of-the-art technologies, including UAVs and advanced algorithms, is rapidly becoming the new frontier in capturing the multifaceted dimensions of aquatic ecosystems. Although UAVs are increasingly being used in common scenarios in aquatic ecosystems, such as habitat surveys, algal bloom monitoring, vegetation monitoring, and animal behaviour observation, K. Wu *et al.* (2019) emphasised that the potential of these technologies to revolutionise ecosystem monitoring remains understudied, especially in the integration of different types of UAVs for comprehensive multi-scale monitoring.

The work of scientist C. Yang (2022) indicates that combining aerial photographs with specific limnological support provides a comprehensive approach to assessing the state of the estuary. Thus, some studies address a number of limnological aspects related to the ecological status using UAV imagery; for example, the dynamics of helophytes (*Phragmites*) in estuaries, submerged macrophytes in shallow estuaries, or algal blooms in reservoirs and estuaries. The aim of this work was to present the results of using drones in the context of monitoring estuary waters using the example of the Tiligul Estuary.

✓ Materials and Methods

The object of this study was the Tiligul Estuary, located in the Mykolaiv region. Like most estuaries in the Northern Black Sea region, the Tiligul Estuary has traditionally been subject to significant anthropogenic influence. Figures 1-2 show the geographical location and bathymetric map of the Tiligul Estuary.

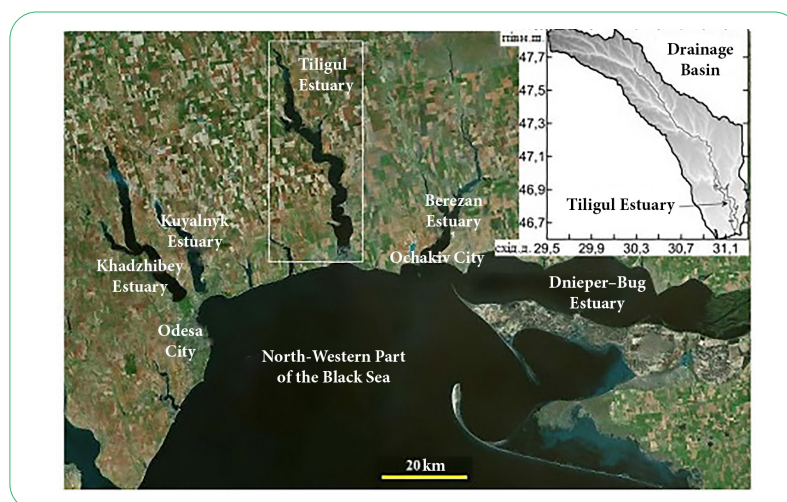


Figure 1. Geographical location of the Tiligul Estuary and its catchment basin

Source: created by the authors based on D. Kushnir & Y. Tuchovenko (2021)

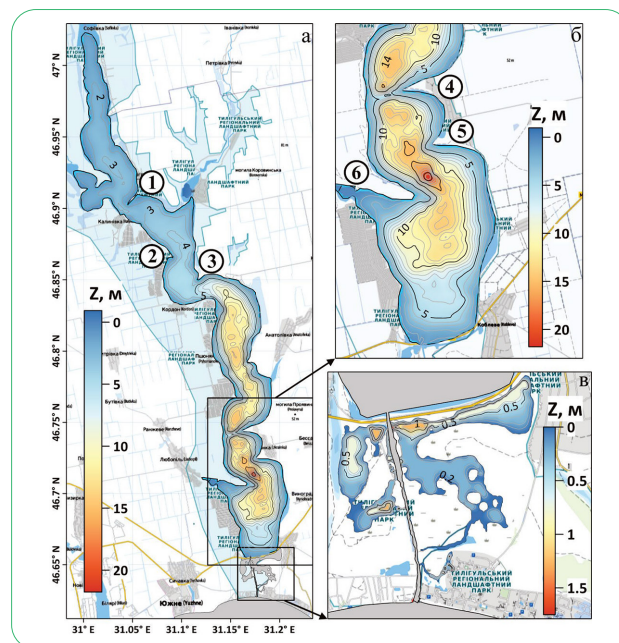


Figure 2. Bathymetric map of the Tiligul Estuary (isobaths in metres)

at a water level of minus 0.4 mBS. WGS-84 horizontal coordinate system

Note: 1 – Lyubopil Spit; 2 – Chervonoukrainska Spit; 3 – Chilova Spit; 4 – Ranzeva Spit; 5 – Anatoliivska Spit; 6 – Kordonska Spit; 7 – Shyrokyina Spit; 8 – Kalynivska Spit; 9 – Strilka Spit

Source: created by the authors based on D. Kushnir & Y. Tuchkovenko (2021), L. Hurets *et al.* (2021)

In this study, a DJI Phantom 4 Pro drone was used to take aerial photographs of the relevant sampling area. The drone was equipped with a 20-megapixel camera. The attached camera is capable of eliminating shutter distortion when shooting fast-moving objects or flying at high speeds, resulting in sharp and vivid photos and videos (Zhang *et al.*, 2023). This equipment can withstand wind gusts of 6 m/s. A Sony Alpha ILCE-5100 camera with a resolution of 20.0 Mpx was used. Possible eutrophication at each sampling point was analysed by processing and interpreting visually and digitally. The orthorectified mosaic served as a platform for creating the NDVI image. To improve the concept of spatial distribution of NDVI in the estuary, only parts of the sampling point

area were covered. A colour composite image was created, which highlighted changes in index values (Mokin, 2005).

Figure 3 shows a map of the Tiligul estuary in the area of protected sand spits with examples of trajectories that the quadcopter must follow for monitoring studies. In particular, the green outline marks the area of artificial reef research; the yellow outline marks the research of vegetation cover, including areas of red-listed species, monitoring of violations of the protection regime; the blue outline marks bird counting. Figure 4 shows a block diagram including the main stages of image acquisition and analysis that are followed to obtain a useful geomatics product for assessing the level of eutrophication.

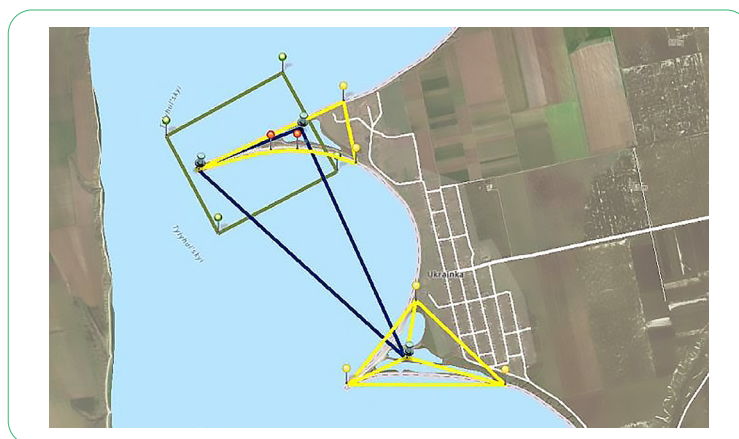


Figure 3. Map showing possible quadcopter trajectories for environmental monitoring and sampling points for analysis

Source: created by the authors

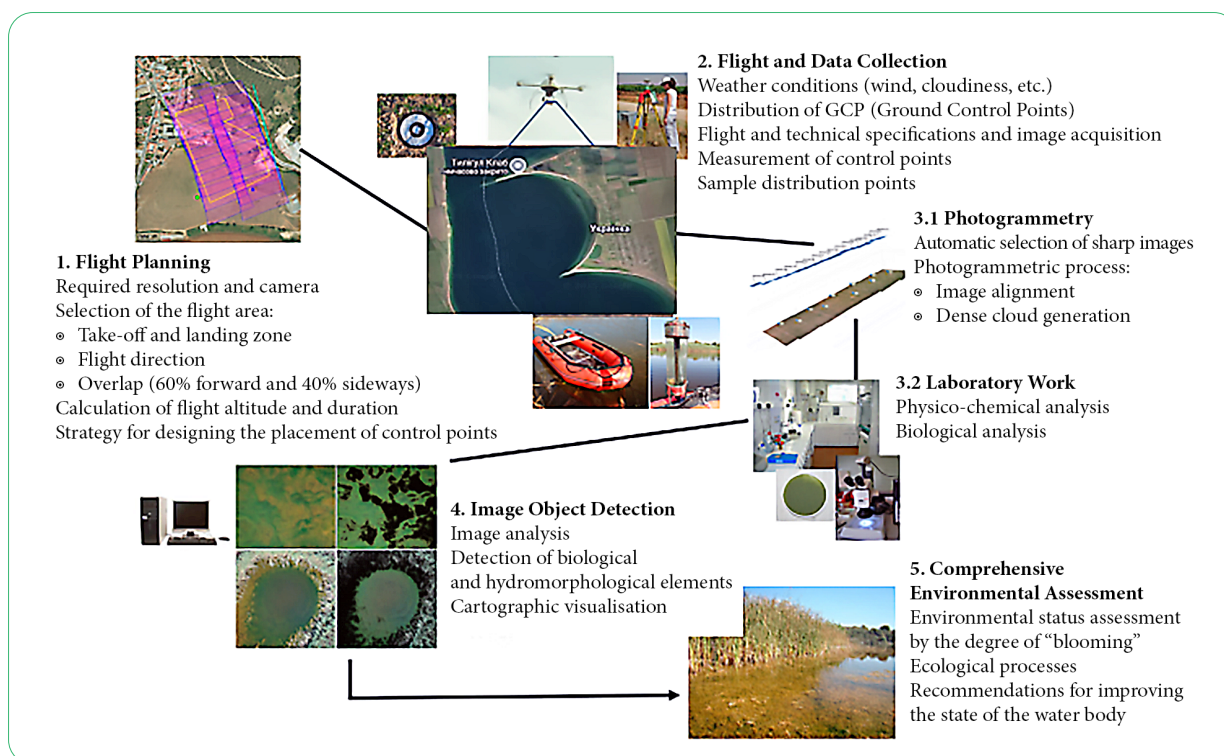


Figure 4. Block diagram showing the main steps in acquiring and analysing images to obtain a geomatics product.

GCP, ground control point; RTK GPS, real-time kinematic global positioning system

Source: created by the authors

The ground sampling distance (GSD) was calculated to obtain a target image resolution of 2.5 cm based on the camera's focal length, taking into account the maximum flight altitude of 120 m in accordance with Spanish airspace regulations. Ten targets (radius 0.20 m) were evenly distributed and measured in the flight area to obtain final georeferenced images (orthoimages) (Zou *et al.*, 2014). The location of the target centroids was measured using a Leica Global Positioning System (GPS) 1200 (Leica Geosystems AG, Heerbrugg, Switzerland) linked to a permanent Global Navigation Satellite System (GNSS) reference station (ERGNSS, 2008). The calculated accuracy of the GNSS real-time kinematic (GNSS-RTK) system was 0.02 m for planimetry and 0.03 m for altimetry (Ownby *et al.*, 2021).

Flights and image processing were performed according to the methodology proposed by J.I. Córcoles *et al.* (2013) and D. Hernández-López *et al.* (2013). Eight UAV flights were conducted during the annual cycle from July 2023 to July 2024. Flights began around noon to minimise solar glare and shading, as well as to optimise visibility conditions for groundwater and submerged vegetation, and to maximise visibility of the deep water column. Image processing included automatic selection of non-blurred images and the following photogrammetric process: photo alignment, dense cloud construction, grid construction, and texture construction. For each flight, an orthomosaic of georeferenced RGB images was created for the main purpose of quantifying the total macrophyte coverage in the estuary and the degree of eutrophication (Sidabutar *et al.*, 2020).

The normalised difference turbidity index (NDTI) was used to determine different degrees of turbidity and was calculated according to S.H. Patel *et al.* (2018):

$$NDTI = \frac{(\text{Red Band } 1 - \text{Green Band } 2)}{(\text{Red Band } 1 + \text{Green Band } 2)}. \quad (1)$$

From the orthophoto with georeferencing, the normalised difference vegetation index (NDVI) image was used for the entire sampling point from the index adaptation, as shown in the equation (2):

$$NDVI = \frac{\text{Band } 4 - \text{Band } 1}{\text{Band } 4 + \text{Band } 1}, \quad (2)$$

where Band 4 – the near-infrared band; Band 1 – the red band.

The NDVI values for the sampling points were obtained by linear regression of the Landsat 8 OLI 0.655 μm /0.56 μm (Band 3/Band 2) ratio with the natural logarithm of the measured NDVI values. A polynomial equation was used to calculate the NDVI values for each sampling point based on the results of the Landsat C3/C2 band ratio (Foste & Vaneekhaute, 2021):

$$(\text{NDVI}) = 7.1354(\text{C3/C2})^2 - 11.761(\text{C3/C2}) + 5.2004. \quad (3)$$

Several studies that used NDVI to determine the eutrophic status of water bodies were used to calculate NDVI values. The NDVI values were also used to correlate with chlorophyll-a (Chl-a) concentrations. The study also

demonstrated the use of Landsat 8 OLI band ratio data to predict Chl-a concentrations. A correlation model between NDVI values and N and P concentrations was identified to compare field measurement data with remote sensing data. The Trophic Status Index (TSI) describes the algae content in estuary water. The Carlson equation is used to calculate the trophic status of sampling points in the Tiligul Estuary with Chl-a concentration values. As mentioned, the NDVI has a strong linear dependence on Chl-a values. Therefore, the TSI can be calculated (4):

$$\text{TSI NDVI} = 10 [6 - (2.04 - 0.68 \ln_{(\text{NDVI})}) / (\ln^2)]. \quad (4)$$

To calculate the TSI, input values obtained using linear regression between the obtained NDVI data and the B3/B2 ratio of Landsat 8 OLI images are used, since the blue-green band ratio is commonly used in oceanic and moderately turbid coastal waters. The authors of this study also considered nitrogen and phosphorus as some of the most important elements for the life of microorganisms. When determining the total phosphorus content, the samples were not filtered or preserved. The duration of the period between sampling and analysis is not regulated. Immediately before the study, the sample was vigorously shaken and then mineralised. In the case of determining the total content of dissolved phosphorus compounds, the water was pre-filtered through a membrane filter with a pore size of 0.45 μm .

The samples were mineralised using potassium persulphate, which oxidises organophosphorus compounds

to oxidation state +5 in an acidic environment, forming orthophosphate ions PO_4^{3-} . The latter were determined photometrically. The method is suitable for the analysis of colourless and slightly coloured estuarine waters. The indophenol method was used to determine the nitrogen concentration in estuary water. This spectrophotometric method is based on the interaction of ammonia with phenol and hypochlorite, resulting in the formation of indophenol, which exhibits a distinct blue colour in an alkaline environment. The highest colour intensity occurs in a solution containing 0.3 M NaOH and 0.8% phenol. The colour intensity is measured at a wavelength of 625 nm. When analysing solutions containing ammonia at a concentration of 1 ppm, the standard deviation of the results is 0.03 ppm.

Results

Analysis of orthophotos ensures that the images cover the entire sampling area. High NDVI values indicate a greater difference between red and near-infrared radiation, while low NDVI values indicate a small difference between red and near-infrared signals (Mažeikienė & Šarko, 2022). This situation occurs when there is little photosynthesis or when there is very little reflection of light in the near-infrared range. It can be seen that all NDVI values for water from all sampling points are in the middle range. This indicates that the estuary water has experienced a state of low photosynthetic activity, and the chlorophyll level in the estuary water is average (Da Costa *et al.*, 2020). The average NDVI value obtained as shown in Table 1.

Table 1. Average NDVI values

Date of observations	Sampling point	NDVI
27 July 2023	1	0.40
	2	0.50
	3	0.38
	4	0.47
8 November 2023	1	0.38
	2	0.41
	3	0.34
	4	0.40
5 March 2024	1	0.37
	2	0.44
	3	0.36
	4	0.40
18 June 2024	1	0.37
	2	0.41
	3	0.36
	4	0.42

Source: created by the authors

It can be seen that sampling points 2 and 4 have higher NDVI values for the four sampling dates, which means that these two sampling points have slightly higher chlorophyll levels compared to the other sampling points. NDVI

values can be observed by the colour shade in the images to show different NDVI levels from the side, as shown in Figures 2-5. A darker colour means a high NDVI value and contains a large amount of chlorophyll (Fig. 5).

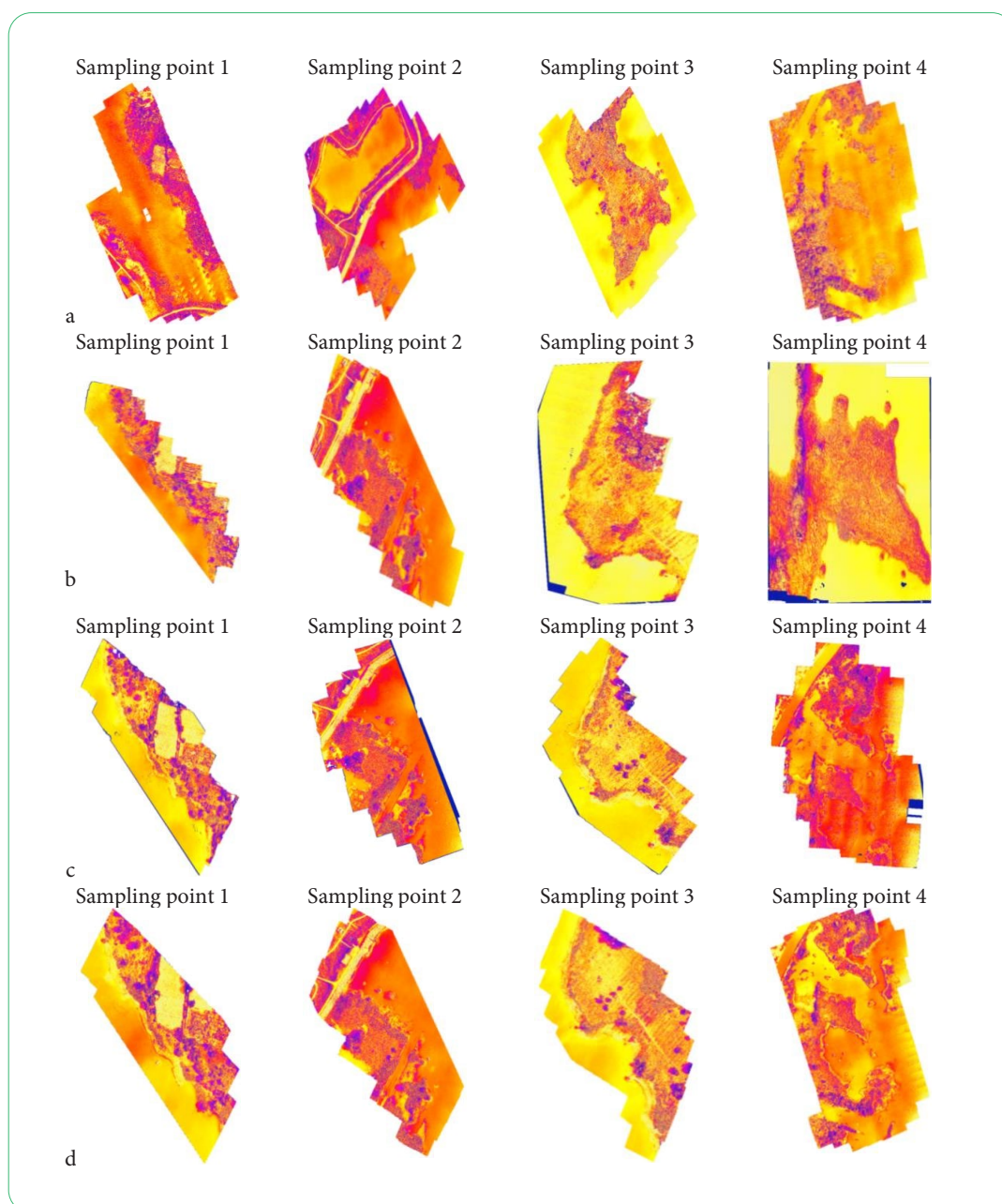


Figure 5. Images of NDVI in different areas of the sample

Note: a – 27 July 2023; b – 8 November 2023; c – 5 March 2024; d – 18 June 2024

Source: created by the authors

Although some sampling points have low NDVI values, the colour becomes darker compared to sampling points with higher index values. This is due to the reflection coefficient of red light in the near-infrared range, which makes the colour darker (Zhang *et al.*, 2023). However, this will not have a significant impact or a large difference in the NDVI value, which will not affect the results (Costa *et*

al., 2019). The pixels that appear in the NDVI were identified as vegetation, and this was associated with water turbidity. The colour tone in the images reflects different levels of turbidity from the side, as shown in Figure 6. While the NDVI values are in the middle range, the NDTI values are also in the middle range, which does not indicate a high level of turbidity.

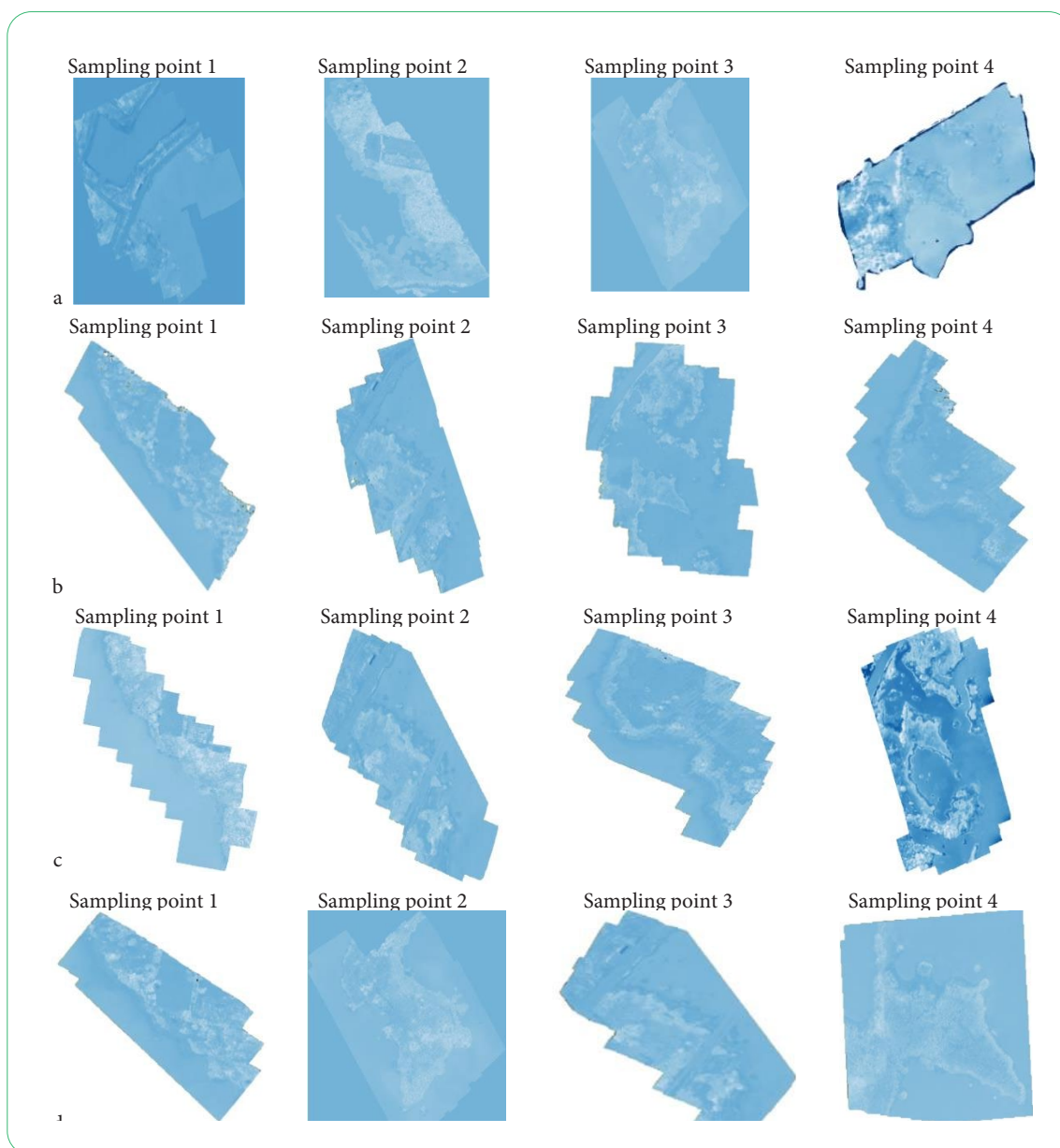


Figure 6. Images of different areas of the estuary

Note: a – 27 July 2023; b – 8 November 2023; c – 5 March 2024; d – 18 June 2024

Source: created by the authors

When comparing the samples, sampling point 4 is more turbid. Higher NDTI values were recorded in the area near the estuary coast due to the interference of aquatic vegetation. Higher turbidity values can be explained by backscattering in the estuary water column, which causes an increase in suspended particles (Denisova *et al.*, 2020). From this point of view, the proposed method is more effective for studying the turbidity of water bodies than conducting measurements on site, which would be very expensive and difficult. As shown in Figure 7, the correlation model produces the best result, which was a second-order polynomial function curve returning a correlation a R^2 equal to 0.7115. This revealed an acceptable linear dependence with a correlation R^2 equal to 0.51 (Aguilar-Ascon, 2020).

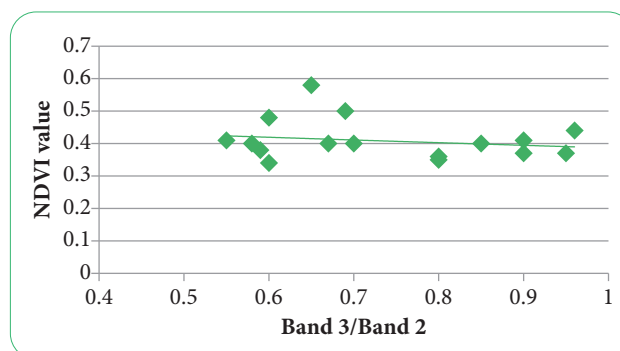


Figure 7. Correlation model between NDVI values and Band 3/Band 2

Source: created by the authors

Since the data on the Landsat 8 OLI and NDVI band ratios have a linear dependence on Chl-a, this study demonstrated a correlation between NDVI and the 0.655 μm /0.56 μm band ratio (Band 3/Band 2). This indicates that NDVI may be equivalent to Chl-a concentration in this particular case.

As a result, the regression line showed a strong relationship between NDVI and the 0.655 μm /0.56 μm band ratio, returning a correlation R^2 of 0.7115 (Ajala *et al.*, 2023). The trophic status of water bodies can be evaluated based on the TSI value calculated as shown in Table 2.

Table 2. Trophic status index (TSI) for all sampling points

Date of observations	Sampling point	TSI
27 July 2023	1	21.54
	2	21.09
	3	21.29
	4	22.70
8 November 2023	1	21.15
	2	21.29
	3	20.41
	4	21.80
5 March 2024	1	20.82
	2	20.74
	3	20.75
	4	21.63
18 June 2024	1	20.90
	2	21.65
	3	20.70
	4	22.49

Source: created by the authors

Based on the calculated TSI values (20-40 TSI), all sampling points can be considered mesotrophic estuaries. This indicates that the sampling area has some algae turbidity, which reduces its aesthetic appeal. However, this condition will not lead to oxygen depletion in deep water horizons and is safe for hydrobionts under these conditions. The results showed that vegetation indices based on UAV images are similar to those obtained from ground sensors and cameras. This study also demonstrates the applicability and reliability of NDVI as an important tool for monitoring water quality in aquatic environments. Nitrogen and phosphorus are the main nutrients in the

eutrophication process; therefore, it is important to determine the concentration of nitrates and phosphates in water bodies. Eutrophication begins when the concentration of nitrogen in water reaches 0.3 mg/L and the concentration of phosphorus reaches 0.02 mg/L (Ownby *et al.*, 2021). From the results presented, it can be seen that the concentration of nitrates and phosphates at all sampling points exceeds 0.3 mg/L and 0.02 mg/L, respectively. These values are presented in Table 3. They show that the sampling area is in a mesotrophic state with slight eutrophication. The excess of nutrients promotes algae growth in this location (Ajala *et al.*, 2023).

Table 3. Concentrations of N and P at all sampling points

Date of observations	Sampling point	Nitrates, NO_3^- (mg/L)	Phosphates, PO_4 (mg/L)
27 July 2023	1	0.15	1
	2	0.43	0.9
	3	0.06	0.6
	4	0.44	1.9
8 November 2023	1	0.13	0.8
	2	0.45	1.1
	3	0.04	0.5
	4	0.41	1.7
5 March 2024	1	0.11	0.7
	2	0.43	1.3
	3	0.05	0.3
	4	0.42	1.6
18 June 2024	1	0.09	0.6
	2	0.43	0.9
	3	0.06	0.4
	4	0.44	1.7

Source: created by the authors

For the correlation between NDVI values and N concentration, it has an inverse correlation R^2 equal to 0.7004, while the correlation R^2 between NDVI values and P concentration is 0.7079. From the correlation model created, it can be seen that P concentration and N concentration have almost the same relationship to NDVI, but in this study, the correlation of P concentration is slightly higher, i.e., high P concentration can lead to high Chl-a concentration and cause eutrophication. This statement was confirmed by research in the work of S. Steffanni *et al.* (2022) conducted on mitigating estuary eutrophication. They argued that to mitigate eutrophication, phosphorus content should be reduced instead of nitrogen. Although controlling nitrogen content also failed to eliminate the reduction in estuary eutrophication, reducing phosphorus content is more important than reducing nitrogen content. The main limitation of the method used in this study was wind speed. Wind tolerance depends on the equipment, in particular its size and weight. With the equipment used here (Microdrones md4-1000, 1.2 kg), flights were performed at wind speeds below 2 m/s. Higher wind speeds can result in blurred images. During the study period, flights were not possible on 12.3% of days due to unfavourable weather conditions, such as high wind speeds. Cloud cover and lighting also affect the results.

In the work of M.W. Letshwenyo & T.V. Sima (2020), it was recommended to perform flights at noon, around 12:00 solar time. Water transparency or turbidity is the main limitation associated with the condition of the water body, which affects the maximum depth visible in UAV images. As a rule, RGB cameras are used under normal lighting conditions and clear water. As noted in the work of C.A Knight (2021), submerged lake vegetation can be classified to a depth of 2.5 m, but changes in turbidity can affect the maximum resolution in terms of depth. In the studied water body, features at a depth of 4 m were detected under clear water conditions, making this methodology very useful for detecting lake stratification processes and for mapping deep-water macrophytic communities.

In the work of S.O. Akinawo *et al.* (2023) confirmed that eutrophication caused by nitrate and phosphate runoff from agricultural land, wastewater from aquaculture ponds, and municipal and industrial discharges is a serious problem due to its significant contribution to socio-economic and environmental health problems. In the work of P.C. Sonarghare *et al.* (2020), it was reported that the emergence of a dead zone due to the effects of eutrophication (consisting of algal blooms and hypoxia) leads to the loss of aquatic biodiversity. Algal blooms are sometimes referred to as “red or brown tides” depending on the colour of the algae, and the organism responsible for red tides is called cyanobacteria. In addition, it has been noted that cyanobacteria produce harmful substances, such as off-flavours and toxins, which are potentially dangerous to the health of both humans and wildlife. Furthermore, C.A. Knight (2021) confirmed that cyanobacterial blooms are one of the serious consequences of eutrophication, causing coastlines and as well as boat hulls with a foul-smelling film, leading to odour and taste problems in water bodies,

thereby rendering them unsuitable for desired use due to their potential danger to wildlife and the population.

In addition, environmental studies conducted in European countries between 2015 and 2021 showed that, according to estimates, only 40-60% of the nitrates and phosphates applied in fertilisers were used by plants. The remaining percentage is reportedly washed into runoff that reaches water bodies, with a phosphate load into European seas of 0.26-0.30 TgP/year (Matei & Racoviteanu, 2021; Pytka-Woszczyło *et al.*, 2022). Further research by L.P. Asututi *et al.* (2022) on the level of eutrophication in the Jatiluhur reservoir, conducted in 2022, showed that the trophic status index (TSI) and trophic index (Trix) exceed 4 and 50, respectively. This indicates an eutrophic-hypertrophic level, characterised by high chlorophyll-a and total phosphorus content in the Jatiluhur reservoir. Based on the study, the following can also be said. A fairly effective method against water “blooming” in Europe is the use of modern LG Sonic ultrasonic technology. This method was studied in the work of S.H. Melnyshenko *et al.* (2023). By 2025, this technology will be used in 55 countries around the world. It is recognised as environmentally friendly and highly effective, eliminating algae and blocking their further growth to the “blooming” stage. At the same time, LG Sonic is completely safe for fish and humans.

A biological method of combating water eutrophication, often used in artificial reservoirs, has also demonstrated high efficiency in European countries. The essence of this method is to introduce herbivorous fish into water bodies, which consume blue-green algae, thereby reducing the intensity of “blooming”. This method not only improves the ecological condition of the water body, but also provides an opportunity to breed fish economically without spending money on feed. Competition for space and resources in the context of sustainable aquaculture development involves the development of closed recirculation systems, the use of offshore farms, including cages, platforms and ropes for shellfish farming, and the integration of future aquaculture projects into a comprehensive zoning and management strategy. Strategic management is key to the recovery and progress of Ukraine's fisheries. Its effectiveness depends on the correct choice of strategic development vector, taking into account specific political, organisational and economic conditions and opportunities, as well as the development of effective regulatory mechanisms.

✓ Conclusions

The use of remote sensing by UAVs in monitoring the eutrophication process offers many advantages over conservative monitoring methods. The results of this study allow establishing – a correlation between the data for the NDVI image obtained during the UAV flight and the estimated values of the Landsat 8 satellite. This study also correlates NDVI values with N and P concentrations obtained from field data. A mathematical model was created and acceptable coefficients of determination (R^2) were obtained, namely 0.7115, using the correlation between NDVI and

the Landsat 8 OLI band ratio using a second-order polynomial function. This second-order polynomial function also provides a mathematical model based on the correlation between NDVI values and N and P concentrations, which has coefficients of 0.7079 for P concentration and 0.7004 for N concentration.

The results can serve as a starting point for further research and expand the study of the impact of other indicators, such as water turbidity, suspended solids, estuary depth, and background influence. Since the TSI value obtained as a result of the study showed the Tiligul estuary to be in a mesotrophic state, this study proposed long-term monitoring of water quality conditions and recommended the implementation of appropriate management plans to support aquaculture and other activities in the estuary. The results of on-site measurements differ slightly from the results of remote sensing. This is because algae growth is

sometimes dominated by light attenuation from inorganic turbidity. Thus, this discrepancy illustrates the need to develop a specific method that depends on the specific conditions of the estuary during the study. It was emphasised that the use of alternative tools in monitoring aquatic environments is particularly important for the application of preventive and corrective measures that can be taken to minimise socio-economic impacts.

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Сучасні методи моніторингу лиманних акваторій на прикладі Тилігульського лиману

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✓ **Анотація.** Ручний моніторинг стану евтрофікації водних об'єктів, таких як лимани, є досить складним завданням. Технологія дронів може бути використана для допомоги в моніторингу будь-яких водойм. Це дослідження було проведено з метою застосування методів дистанційного зондування на основі безпілотних літальних апаратів (БПЛА) для отримання показників евтрофікації у водах Тилігульського лиману. Основу інформації становлять дані, зібрані дронами, стосовно рівня евтрофікації та стану морських просторів. Для збору даних з повітря використовувався дрон DJI Phantom 4 Pro. Для тестування було обрано чотири точки відбору проб, де оцінювали нормалізований індекс різниці рослинності та нормалізований індекс каламутності різниці. Також були отримані дані Exsitu, такі як концентрація нітратів і концентрація фосфатів. Було розраховано індекс трофічного стану, який описує вміст водоростей в лимані. Гіперспектральні зображення БПЛА були орто-випрямлені та геоприв'язані в програмному забезпеченні Agisoft PhotoScan та оцінці значення нормалізованого різницевого вегетаційного індексу в ArcGIS. Результати показали кореляцію між значеннями індексу різниці рослинності та концентрацією азоту та фосфору зі значеннями коефіцієнтів 0,7079 для концентрації фосфору та 0,7004 для концентрації азоту відповідно. Це дослідження підтвердило застосовність дистанційного зондування для управління водними ресурсами за допомогою БПЛА, що характеризується як швидка та проста методологія. Запропоновано якісну оцінку й контроль параметрів довкілля під час розв'язання задач екологічного моніторингу морських акваторій і прибережжя. Зазначено, що методи математичного та імітаційного моделювання сприяють формуванню функціональних й інформаційних моделей, а також застосовуються методи системного аналізу для виявлення структурних зв'язків між компонентами складних систем. Отриманні результати проведеного дослідження дадуть змогу в подальшому використовувати БПЛА та інші способи дистанційного зондування для моніторингу та прогнозування стану лиманних та морських акваторій

✓ **Ключові слова:** моніторинг морського середовища; безпілотні літальні апарати; естуарій; управління прибережною зоною; евтрофікація



Integration of satellite monitoring for flood risks forecasting on the example of the Dniester's Flood Surveying Site

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✓ **Abstract.** The relevance of the study lies in the development, improvement and practical implementation of a geoinformation approach to flood risk forecasting within the Dniester flood control area by integrating satellite monitoring, spatial analysis and interpolation methods. The study was aimed at creating an effective system for identifying potentially dangerous areas, analysing floodwater pollution and assessing the impact of climate change on hydrometeorological processes in order to increase environmental safety and ensure sustainable risk management at the level of territorial communities. Mapping of Quaternary deposits, geomorphological levels and landscape structure was carried out, and a forecast map of flooding of territories with water rising by 1, 3, 5 and 10-12 meters was constructed. The final result was a 3D map, which is presented as an interpolated surface, created using the inverse weighted distance method. The optimal intervals of the value and size of the cells were selected: the obtained result allows not only to analyse the risks of flooding, but also to draw up reports with visualisation of data stored in the form of graphic images. For the first time, a map of the ecological risk of flooding of the Dniester flood control site by catastrophic floods was created for the Dniester Valley and adjacent territories of Podillia and Prykarpattia. The study showed that the process of flooding of the Dniester Valley occurs sequentially: first, the low floodplain is flooded (water rise +1 m), then the middle (+3 m), high (+5 m) floodplains and, finally, the first suprafloodplain terrace (+10-12 m). Based on the identified patterns, a system for predicting the rise of water during floods was developed. In addition to forecasting, this system performs the function of notifying the population about catastrophic manifestations of water elements

✓ **Keywords:** interpolation; modeling; remote sensing; geographic information systems; water resources management

✓ Introduction

The relevance of the research topic is explained by the increasing frequency of severe floods in the Dniester regions due to climate change, suboptimal water use and disruption of natural hydrological systems. Such floods pose a threat to human life and health, destroy valuable natural and social resources and negatively affect ecosystems. The Dniester Valley is one of the most urbanised and valuable areas of Ukrainian Podillia, characterised by a high level of flood

risk. Protecting the population from catastrophic floods and assessing the risks associated with them is a priority area of environmental and social research in this region.

Recent studies highlight a wide range of problems related to flood forecasting and environmental safety. According to researchers O. Adamenko *et al.* (2020), the role of geographic information systems and satellite monitoring in modeling flood risks is considered. In particular,

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the works highlight the importance of integrating remote sensing for operational monitoring of watersheds and assessing the impact of climate change on the hydrological regime of territories. Ecological security is defined as the state of the environment that ensures comfortable living conditions for the population, sustainable development and restoration of ecosystems disrupted by anthropogenic processes. Researchers O. Adamenko *et al.* (2022) substantiated the structure of ecological security, which includes computerised and geoinformation systems for predicting and minimising the consequences of flood situations. This study proposes to combine existing approaches into a single ecological geoinformation system that integrates remote sensing methods to increase the level of ecological security in the Dniester Valley.

The studied area, according to researchers P. Lysytsia & O. Mudrak (2022) and A. Dzyba & V. Kyriienko (2024), in geomorphological and morphostructural terms covers fragments of two first-order morphostructures: East Carpathian and Podilsko-Kodrynska. Within their boundaries, second-order morphostructures are distinguished: Outer Carpathian, Precarpathian and Podilsko. Finer zoning into third-order morphostructures, according to the origin, forms and age of the relief, is carried out according to various schemes. The aim of the study was to develop geoinformation models and methods for predicting catastrophic floods in the Carpathian region (Dniester basin) based on the integration of historical, instrumental and satellite data to increase the effectiveness of early warning and minimise risks.

▼ Materials and Methods

The study used historical and instrumentally confirmed data, which was justified by the identification of patterns of flood periodicity. To create a periodisation of catastrophic floods on rivers such as the Dniester, both natural extreme phenomena and their interaction with anthropogenic factors were analysed. In particular, the recurrence of warm (dry) and cold periods and the floods associated with them was considered. The study took into account the stage of development of the Dniester valley and long-term observations of the Dniester river regime at the hydro-post of the city of Halych, since these processes are key for predicting changes in the behavior of the river and developing flood risk management measures. The method of correlation of water flow in the Dniester river (city of Halych), conducted on the basis of long-term observations, was analysed.

To assess flood risks in Galician Transnistria, a geomorphological map of the Dniester flood control site was created. The map was developed by D. Zorin (2022) with the participation of students, under the scientific supervision and editorial support of Professor O. Adamenko *et al.* (2022). The work included field expedition mapping, hypsometric analysis of topographic maps at a scale of 1:10,000, and processing of satellite images using MapInfo software. The use of the MapInfo geoinformation environment ensured accurate processing and visual display of spatial data, which contributes to improving the environmental safety of the studied area.

Thanks to cooperation with the Institute of Telecommunications and Global Information Space of the National Academy of Sciences of Ukraine, the National Space Agency of Ukraine, the Space Information Reception Center in Dunayevtsy, the State Emergency Service of Ukraine, the Dniester Basin Water Resources Management Board, the Ministry of Environmental Protection and Natural Resources, as well as with the involvement of open sources, in particular sentinel-hub.com and media materials, a comprehensive analysis of numerous satellite and aerial photographs was carried out. This made it possible to study in detail the spatial features of the distribution and intensity of the catastrophic floods of 2008 and 2020 in the Western region of Ukraine (Kuzmenko *et al.*, 2019). Also, in order to assess the impact of this extreme flood on the territory of the Carpathian region, the flood limits caused by the western cyclone in July 2008 were simulated. After digitising the flood zone based on the 2020 satellite image, the resulting model was overlaid with the contour of a forecast map developed back in 2015.

To predict the ecological risk of flooding of territories by catastrophic floods, a map was created for the Dniester Valley and adjacent territories of Podillia and Prykarpattia for the first time (Adamenko *et al.*, 2022). This cartographic model, authored by Denis Zorin, became the basis for analysing and forecasting flood situations in the region. To predict the flooding of the territory, it was necessary to create a 3D model. To achieve the desired level of detail, optimal value intervals and cell sizes were selected, which, although increasing the processing time, allowed for more accurate interpolation results. Additionally, transparency, legend, map name, and value elements were configured. The settings were saved as templates for reuse without the need to perform all actions from scratch. After creating the 3D surface, contours were constructed using the 3D View utility. The contour intervals were aligned with the thematic map to ensure consistency in the displayed data. The result allowed not only to analyse the risks of flooding, but also to generate reports with visualisation of the data, which were stored in the form of graphic images.

To predict floods, three-dimensional models of territories were created, which allow assessing the levels of flooding and determining environmental risks. An important stage in this process was the formation of a Grid Image using MapInfo Pro software. Using GIS technologies such as MapInfo Pro, the researchers created interpolated surfaces, constructed contours, and generated flood risk maps. For this purpose, interpolation methods were used, in particular, the inverse distance weighted (IDW) method and the irregular triangle network (TIN). The IDW method provided high modeling accuracy, especially for large amounts of data. This method turned out to be more effective than TIN, in addition, it provides more accurate results and works stably (Stetsenko, 1999; Sosonna *et al.*, 2023). Based on the revealed regularity, a system for predicting water rise during floods (AVIPS-Dniester) was further developed.

Results and Discussion

The analysis of historical materials, chronicles and documents for the period of the 8th-19th centuries shows that climate change often causes catastrophic natural phenomena, including floods, severe winters, early frosts, epidemics and other emergencies. These phenomena had a certain periodicity, which can be used to predict them in the future. The recurrence of warm and cold periods and the associated floods demonstrates cyclicity: droughts occur in the 20s,

60s and 70s of each century, and significant disasters can recur every 300 years. Although modern reports of extreme events are described as “unprecedented” or “unheard of,” historical records show that similar events have occurred in the past. Therefore, studying historical climate processes and their impact on natural disasters helps not only to understand the past, but also to predict future extreme events. This highlights the need to analyse long-term data to develop an effective forecasting and warning system (Table 1).

Table 1. Recurrence of catastrophic floods over the last millennium, according to chronicle and historical data

Year of occurrence of the previous flood	Year of occurrence of the next flood	Interval in years between floods	Year of occurrence of the previous flood	Year of occurrence of the next flood	Interval in years between floods	Year of occurrence of the previous flood	Year of occurrence of the next flood	Interval in years between floods
1	2	3	1	2	3	1	2	3
987	989	2	1681	1686	5	1814	1815	1
989	991	2	1686	1688	2	1815	1820	5
991	1012	21	1688	1689	1	1820	1822	2
1012	1148	36	1689	1700	11	1822	1832	10
1148	1161	13	1700	1702	2	1832	1834	2
1161	1162	1	1702	1703	1	1834	1835	1
1162	1173	11	1703	1705	2	1835	1836	1
1173	1221	48	1705	1706	1	1836	1837	1
1221	1230	9	1706	1707	1	1837	1838	1
1230	1236	6	1707	1708	1	1838	1839	1
1236	1251	15	1708	1709	1	1839	1840	1
1251	1269	18	1709	1716	7	1840	1841	1
1269	1285	16	1716	1717	1	1841	1842	1
1285	1290	5	1717	1718	1	1842	1843	1
1290	1291	1	1718	1719	1	1843	1844	1
1291	1314	23	1719	1721	2	1844	1845	1
1314	1322	8	1721	1723	2	1845	1846	1

Source: developed by the authors

Analysis of previous studies and graphical data shows a certain pattern of recurrence of catastrophic floods. Annual spring floods are a common phenomenon with a one-year cycle. Usually, stronger spring floods occur with an interval of 3-4 years, which can be considered the first phase of periodic catastrophic phenomena. The most significant floods that leave significant consequences are repeated with a frequency of 15-20 years, forming the third phase. These cycles are interconnected: the first phase (3-4 years) is repeated twice within the second phase (5-6 years), while the second phase is included in the third (15-20, sometimes up to 33 years) and is repeated 3-4 times during this long cycle. This periodicity structure is

confirmed by long-term meteorological observations covering the instrumental period since 1881. Both regional and local floods are observed in the Carpathian region. Regional floods cover the entire northeastern macroslope of the Carpathians, while local floods occur only within individual river basins. According to G.I. Shvets, M.I. Kyrlyuk and other researchers (Ali *et al.*, 2020), in the 20th century, catastrophic regional floods on the northeastern macroslope of the Carpathians occurred in the warm season (June-August) in 1911, 1927, 1941, 1955, 1969, 1980, 1998, 2002 and 2008. In Transcarpathia, such phenomena were mainly recorded in the cold period (November-May) in 1926, 1947, 1957, 1970, 1998, 2002, 2008 and

2020. Local floods occur much more often - approximately every 2-3 years. Floods on the rivers of the Carpathian region are formed as a result of intense atmospheric precipitation, which is frequent in this region. However, catastrophic levels of water rise are reached only when the amount of precipitation exceeds 100 mm per day. Instrumental observations of the water resources of this region began in the middle of the 19th century, and systematic data have been available since 1895. Despite the complexity of predicting these phenomena, their increase in frequency is associated with global climate change. The author constructed graphs of global climate fluctuations, and researchers O. Adamenko *et al.* (2022) predicted a flood in 2020 back in 2014. The Dniester River Valley demonstrates a complex geomorphological structure and

development dynamics. The river within the valley it created meanders from one side of the valley to the opposite, going through several stages of its development. First stage: during tectonic uplift of the territory, the riverbed cuts into the root bank, forming a straight path. Second stage: the river goes into lateral erosion, forming meanders, the radius of which can be 18 times the width of the riverbed. This stage is considered the period of maturity of the river. Third stage: during new tectonic activation, the valley area rises again. The river cuts into the root bed, and the old meanders turn into incised ones. The riverbed straightens when the isthmuses between the meanders are cut by the current. The Dniester Valley is in the third stage of its development, which affects the formation of its relief and hydrological regime (Fig. 1) (Davybida *et al.*, 2021).

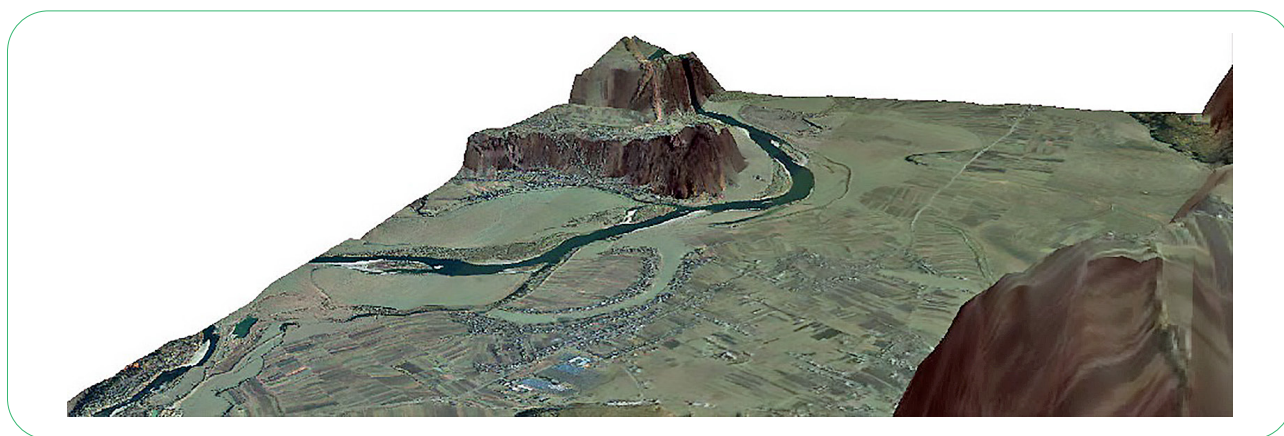


Figure 1. 3D model of a satellite image of the Mariyampil tablet

Note: the distance between the contour lines of elevations above sea level is 1 m

Source: developed by the authors

The right tributaries of the Dniester within the Dniester flood control area – Limnytsia and Lukva – are characterised by uneven flow throughout the year, which leads to a large number of floods. They are caused by both melting snow in the mountains and heavy rainfall. The Hnyla Lypa River and its tributaries have only one high level in spring, caused by melting snow cover. According to long-term observations of the Dniester River regime at the Halych hydro-station, the most characteristic feature of the Dniester River water regime is frequent floods throughout the year. The height of floods near Halych varies within 0.5-5 m. The rivers of the Dniester flood control area, which are right tributaries of the Dniester River, are mixed: in spring, the main source of runoff is snowmelt, from May to November – rain, after which groundwater dominates. In particular, the flow rate of the Lukva River is 141.6 million m³, the flow in low-water years with a provision of 75% and 95%, respectively, is 98.7 and 59.3 million m³. The river's own flow is not regulated. The left-bank tributary of the Hnyla Lypa River is characterised by spring floods. Summer precipitation here does not have a noticeable impact on the river regime, but there are individual significant floods (Mamo *et al.*, 2019; Bilas *et al.*, 2022). An analysis of water

flows in the Dniester River – the city of Halych, conducted on the basis of many years of observations, indicates their stability within 100-200 m³/s. The maximum water flow was recorded in 1943 in the city of Halych – 770 m³/s.

An assessment of the current state of surface waters of the upper Dniester indicates a significant anthropogenic impact on its water regime. The catchment area is home to a large number of settlements, industrial and agricultural facilities. Intensive wastewater discharge and pollution cause deterioration of water quality, siltation and bank collapse. In many places, the land is plowed up to the very banks, which intensifies erosion processes. Domestic wastewater from settlements, farms and social facilities adds to the overall pollution, creating urgent problems for ensuring the ecological safety of the Dniester River basin. To analyse flood risks in Galician Transnistria, a geomorphological map of the Dniester flood control site was created (Fig. 2). This map plays an important role in forming a system for predicting the sequential flooding of the Dniester Valley during catastrophic floods. It serves as a basis for creating ecological flood risk maps and contains information on the morphology, genesis (origin) and age of macroelements of the relief. These operations can be implemented not only in MapInfo, but also in

other GIS software environments, which provides flexibility and versatility of the approach. At this landfill, modeling, forecasting and development of practical measures to prevent catastrophic consequences of water events are carried

out. The results obtained are used not only in the Dniester Valley, but also in other water basins. One of the key research tools was 3D modeling, which provides the possibility of detailed analysis of orographic and hydrological factors.

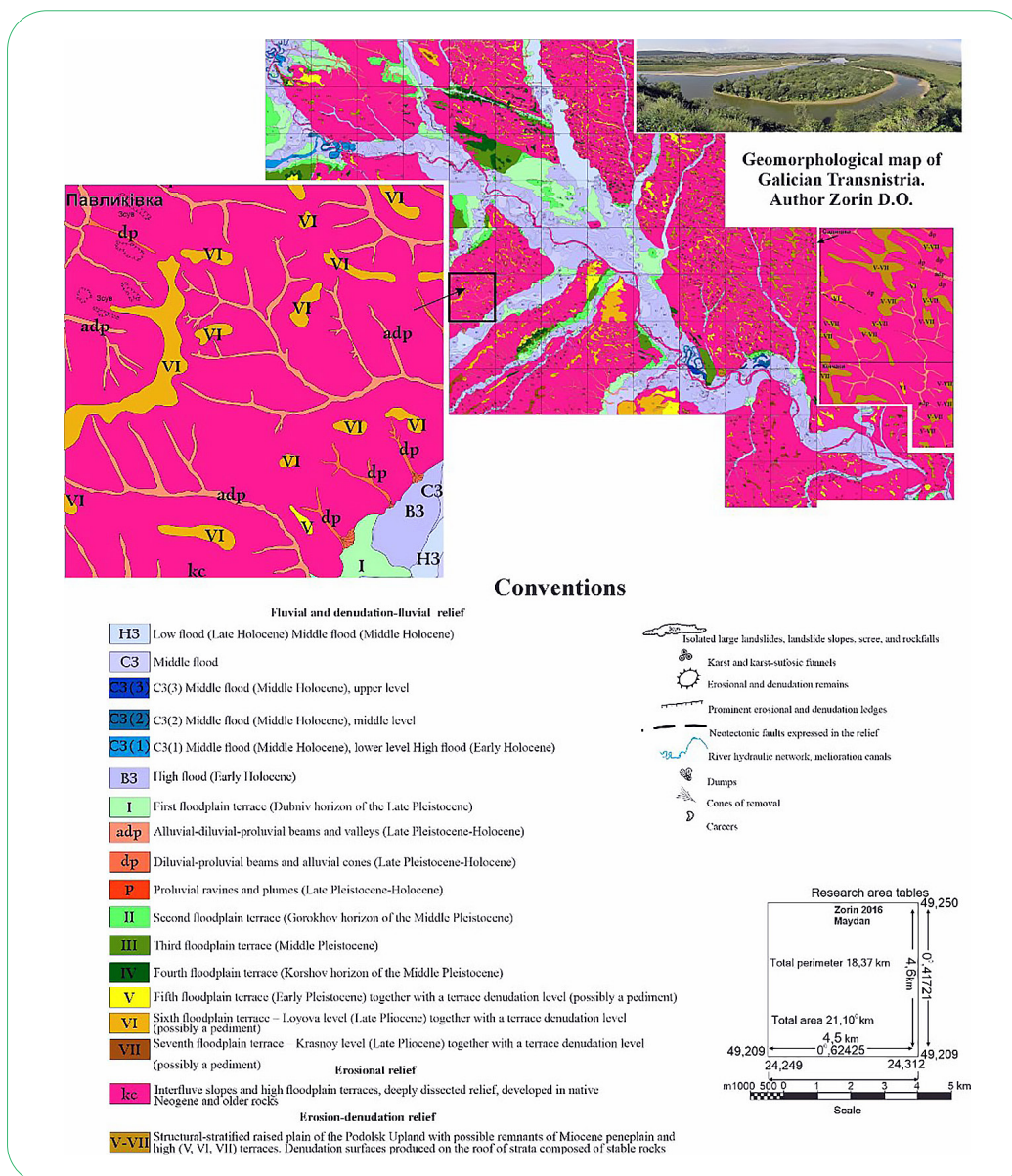


Figure 2. Geomorphological map of Galician Transnistria

Source: D. Zorin (2022)

An important element of the modern flood protection system is risk management, i.e. early prediction of dangerous processes, identification of the main causes, natural and anthropogenic factors of the development of floods and floods, development of measures to reduce them to a favorable level. The main tool of the flood risk management system is a management plan based on maps of the possible development of these dangerous processes. Such maps and plans should be developed for each catchment basin of the watercourse of the appropriate order, taking into account the principles of the basin approach and the

specifics of the hydrological and geomorphological conditions of a particular territory (Kozłowski *et al.*, 2023). The spatial features of the distribution and intensity of the catastrophic floods of 2008 and 2020 in the Western region of Ukraine were studied (Fig. 3-4). Figure 4 presents the vectorised flood boundaries. The study showed that the flooding process of the Dniester valley does not occur chaotically, but sequentially: first, the low floodplain is flooded (water rise +1 m), then the middle (+3 m), high (+5 m) floodplains and, finally, the first suprafloodplain terrace (+10-12 m).

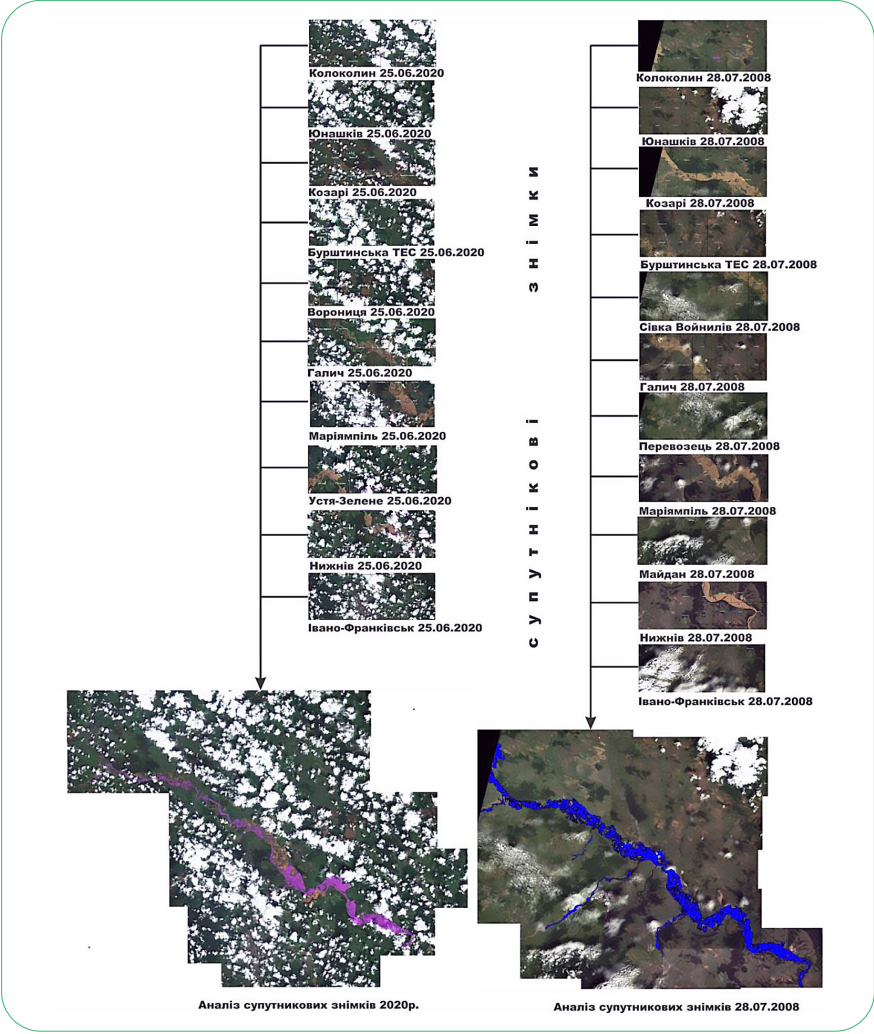


Figure 3. Comparison of satellite images from 2008 and 2020

Source: created by the authors



Figure 4. Vectorised flood boundaries of 2008

Note: satellite image sentinel-hub.com 07/28/2008

Source: developed by the authors

The analysis showed that the boundaries of the predicted and actual flood zones coincided, which confirms the high accuracy of the previous forecasts. These consequences could have been predicted in advance, which would have

allowed measures to be taken to warn the population and minimise damage (Fig. 5). The areas of actual flooding are marked in red, which reflected the scale of the real consequences of the flood.

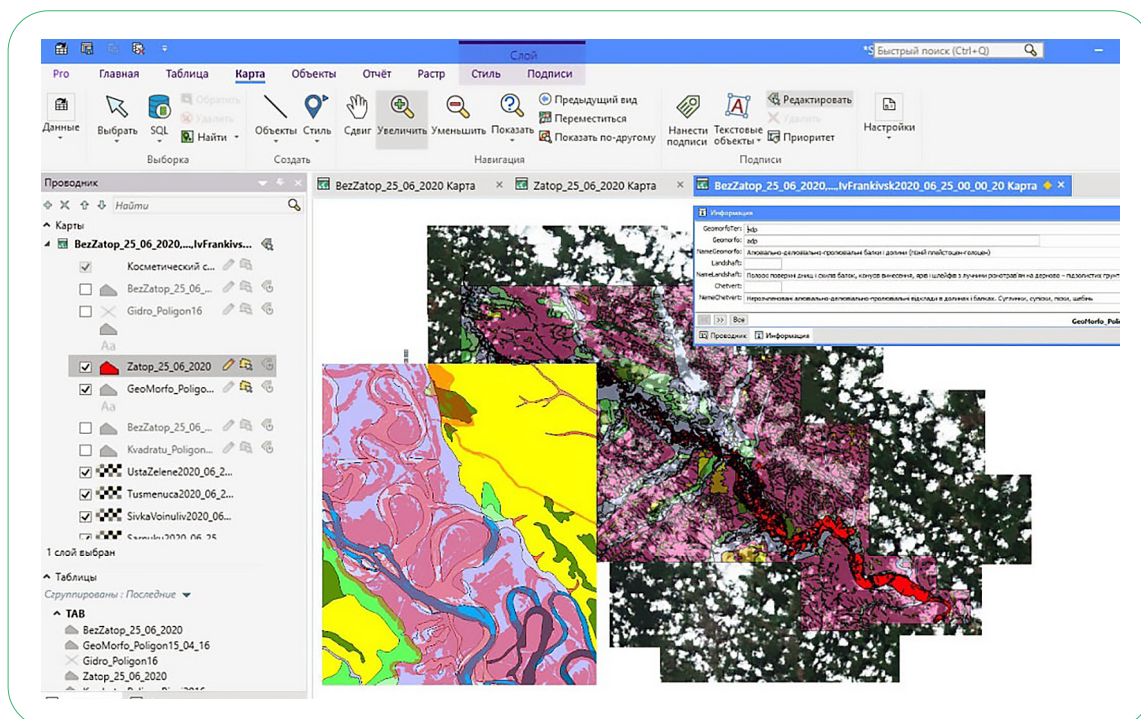


Figure 5. Analysis of satellite images of 06/25/2020 and maps of environmental risk of flooding of territories of 06/15/2015

Source: developed by the authors

Scientists of the Ivano-Frankivsk National Technical University of Oil and Gas (IFNTUNG) are making significant efforts in the study of floods. In particular, on August 4, 2008, the researchers submitted their proposals to the Ivano-Frankivsk Regional State Administration on preventing the consequences of catastrophic floods. At the initiative of the rector of the university, Professor E.I. Kryzhanivskiy, in cooperation with the regional council, state administration and other organisations, the Dniester Scientific, Educational, Production Engineering and Environmental Flood Prevention Range was created with a center in the village of Mariyampil, Halytskyi district, Ivano-Frankivsk region (Fig. 5) (Myrontsov, 2020; Trigub & Domuschi, 2023). This work is long-term and follows the following character: it began back in 2008 after the catastrophic flood, which prompted the creation of the Dniester flood control site. Since then, starting in 2010, research has been conducted systematically. Within the framework of this project, data is accumulated, databases are formed and geoinformation models are created that allow improving the system of flood forecasting and analysis. The work continues as of 2025, providing a valuable basis for flood risk management (Table 1). A 3D model was created to predict the flooding of the territory, which provided a more accurate analysis and visualisation of risks (Fig. 6-7).

The analysis of the satellite image from June 25, 2020 and the ecological risk map of the territories created on June 15, 2015, showed a high correspondence between the predicted flood limits and the actual data. The contours of the flood zones, modeled five years before the event, almost completely coincided with the real limits recorded on the satellite image. This indicates the high accuracy of the applied forecasting methodology and the effectiveness of the integration of geographic information systems and satellite monitoring for flood risk assessment. The obtained result confirms the feasibility of implementing such approaches in the ecological safety and emergency management systems. The symbols of the flood risk zones are shown in Figure 8.

The Automated Information and Measurement Anti-Flood System – Dniester (AVIPS-Dniester) consists of three models – cartographic, mathematical and geoinformation, which must be included sequentially during the development of the flood as separate blocks: 1) automated hydrological post; 2) weather station; 3) telemetric system for transmitting information from hydroposts and weather stations to the crisis center of the State Emergency Service and from it to settlements; 4) marking on the ground in settlements of segments that will be flooded when the water level on the main river rises by 1, 2, 3... 10, 11, 12 m. The development of such models is a key stage in the creation of

long-term regional programs and operational measures to prevent and eliminate emergencies in the Dniester Valley and the Carpathian-Podilskyi region. In addition to forecasting, this system performs the function of notifying the population about catastrophic manifestations of water elements (Fig. 8). At this landfill, modeling, forecasting and

development of practical measures to prevent catastrophic consequences of water elements are carried out. The results obtained are used not only in the Dniester valley, but also in other water basins. One of the key research tools was 3D modeling, which provides the possibility of detailed analysis of orographic and hydrological factors.

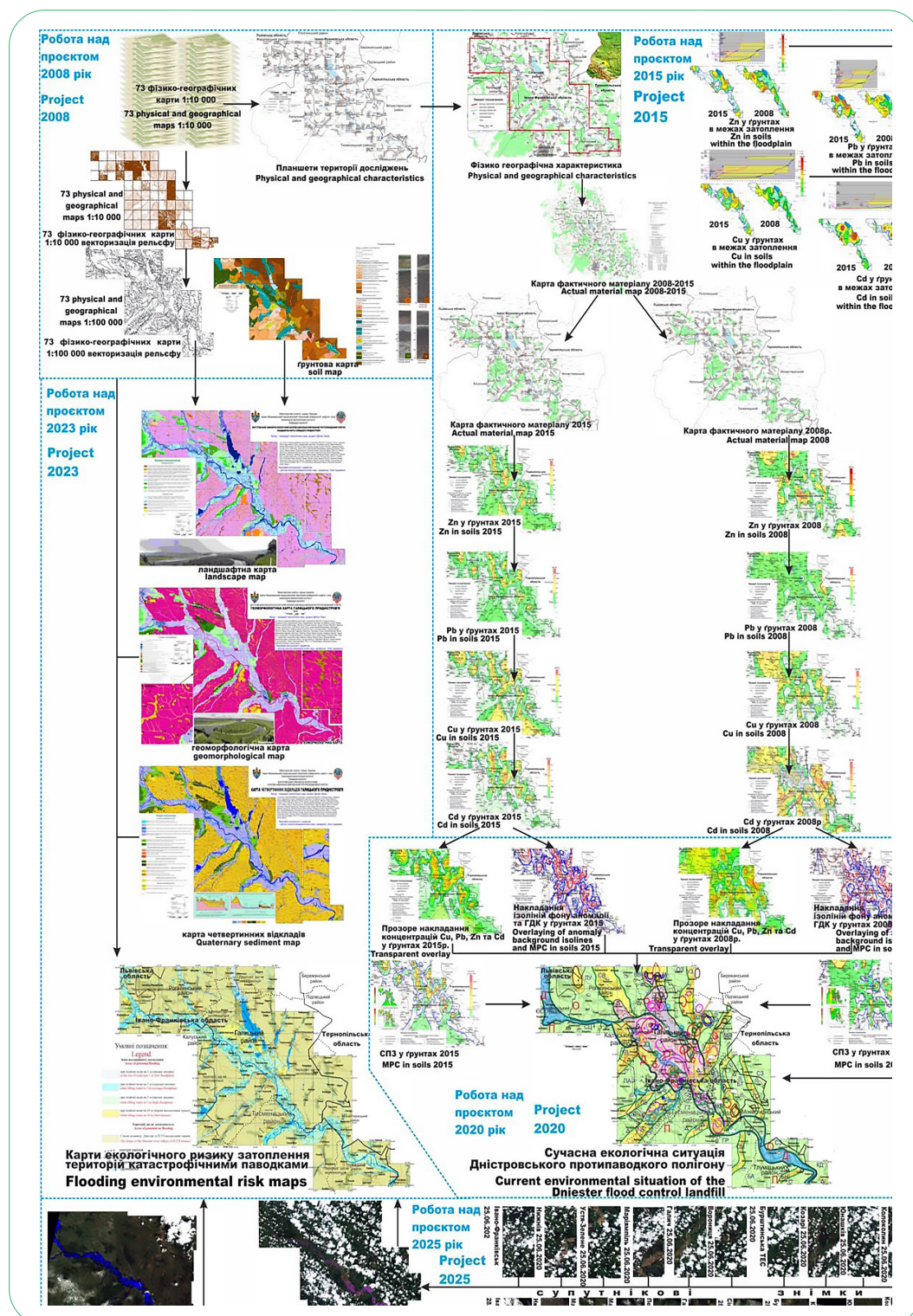


Figure 6. Scheme for creating ecological maps

Source: created by the authors

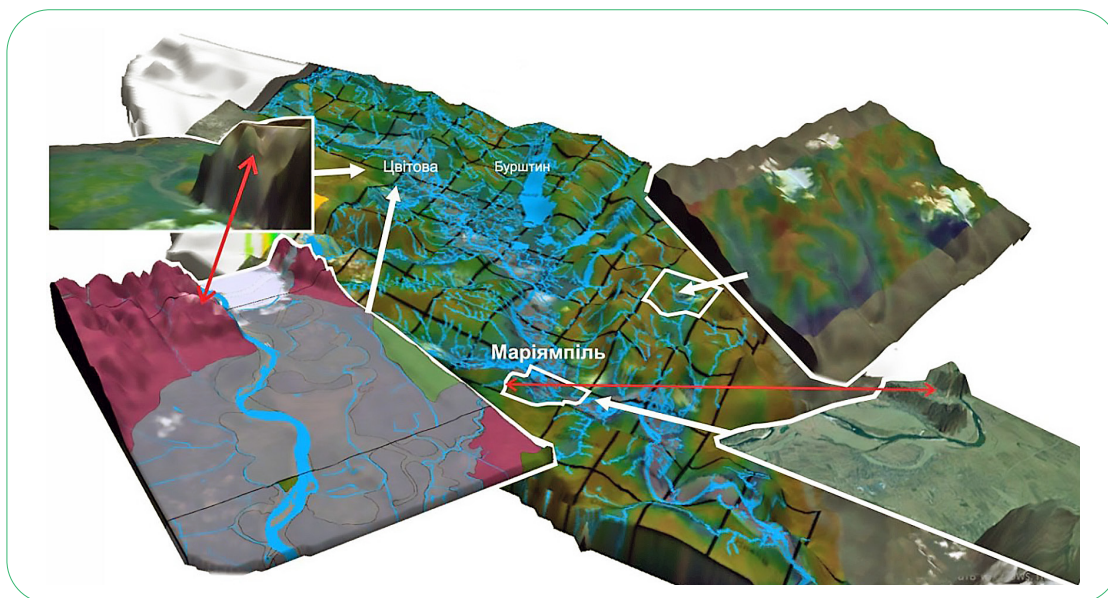


Figure 7. 3D model

Source: developed by the authors

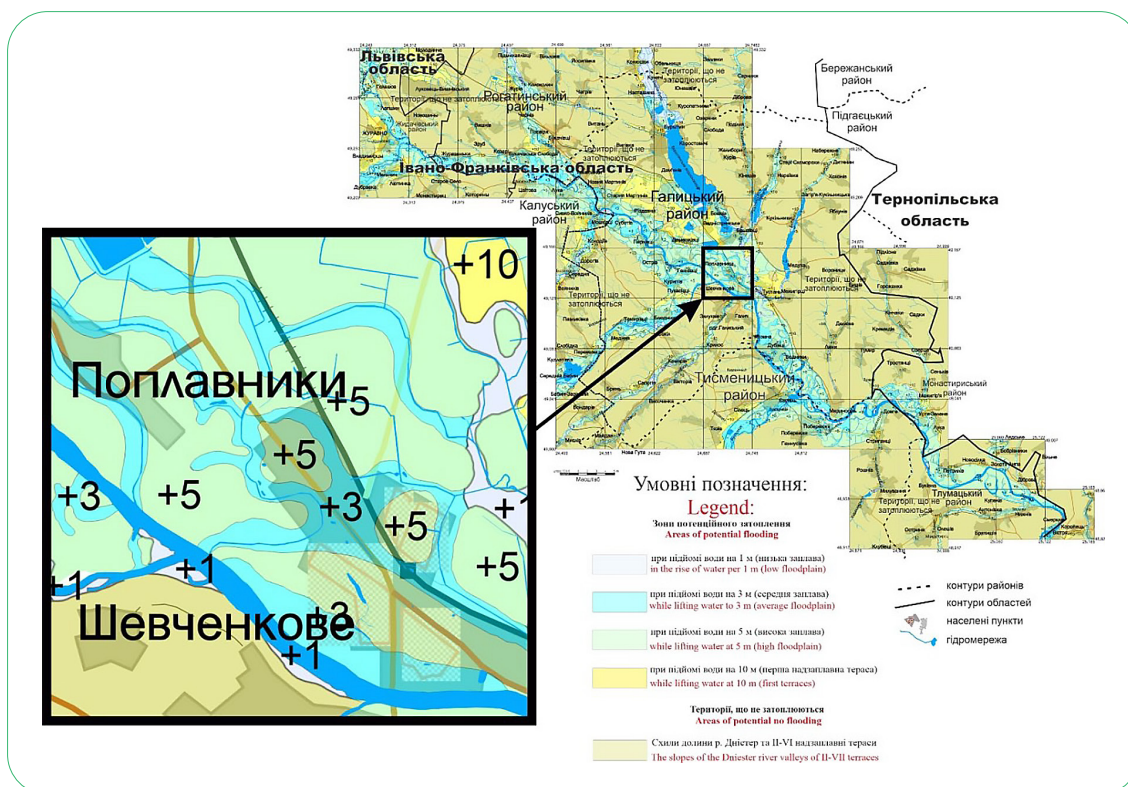


Figure 8. Maps of the ecological risk of flooding of territories by catastrophic floods

Source: developed by the authors

The study of orographic factors affecting the retention of cyclones in the Carpathians, where the bulk of precipitation falls in the Carpathian region, is considered as a possibility of retaining part of the runoff using hydraulic structures. The processes of water accumulation in the cirque-shaped upper reaches of small Carpathian rivers play a key role in the formation of flood waves. In the absence of intercepting hydraulic

structures (dams or water catchments), rain or snowmelt runoff is not delayed in these basins, but rapidly descends to the lower parts of the relief. This leads to increased erosion processes in the channels, destruction of banks, the formation of mudflows and the occurrence of landslides, especially in conditions of overwetting of slopes. Based on 3D modeling, recommendations are provided for reducing these risks.

Modern three-dimensional modeling technologies allow significantly increasing the efficiency of analysing flood formation processes. They provide an accurate representation of the relief, modeling of surface runoff directions, identification of water accumulation zones and potentially dangerous areas. This contributes to better forecasting of flooding, erosion processes and landslides, as well as optimisation of the placement of engineering protection. Thanks to modern 3D modeling technologies, it is possible to significantly improve the understanding of flood formation processes, which is important for preventing their catastrophic consequences and reducing risks for the population and infrastructure (Lou *et al.*, 2023). Recommendations for reducing flood risks based on 3D modeling:

1. Construction and reconstruction of intercepting hydraulic structures: installation of retention dams and water retention structures in the upper reaches of river basins to contain rapid surface runoff; use of floodplain reservoirs for temporary storage of flood waters.

2. Anti-erosion measures on slopes: carrying out afforestation in areas with high erosion risk; development of a terracing system in areas with steep terrain to reduce the force of surface runoff.

3. Optimisation of development and land use: restriction or prohibition of construction in areas identified by the model as high-risk (lowlands, valleys, channel terraces); change in land use type in critical areas (e.g. conversion of agricultural land to nature reserves).

4. Improvement of early warning system: integration of 3D models into monitoring and warning systems, in particular for prompt notification of the population in case of flood threat.

5. Regular updating of hydrological data: conducting periodic terrain scanning (LiDAR) and updating digital elevation models to increase the accuracy of forecasts; monitoring the dynamics of coastlines and flood zones.

6. Ecological reconstruction of river valleys: restoration of old rivers, wetlands and natural floodplains that can act as buffer zones during floods.

7. Community education and formation of emergency action plans: development of local evacuation plans; conducting training for the population on flood response taking into account the risk zones identified by the model.

Forecasting and warning local authorities and the population about floods remain difficult tasks due to the unpredictability of these phenomena and the speed of their development. The experience of previous floods has reached the level of public awareness. Ensuring safety in the Dniester River Valley and its tributaries includes reducing the risk of harmful consequences of catastrophic floods and floods. Floods and flash floods can occur suddenly and reach a peak intensity within a few minutes, which significantly complicates the possibility of early forecasting and effective warning of the population. Therefore, early planning, preparation and implementation of safety measures aimed at minimising risks to people and infrastructure are of particular importance. In such conditions, it is extremely important to know

whether your home is located in a potential flooding zone, as well as to assess the level of safety of staying at home or the need to find another shelter. Residents of risk areas should have a clear idea of the possible threats of this natural phenomenon and always be ready to take appropriate action in case of danger (Malkova *et al.*, 2023; Sysak, 2024).

First of all, it is necessary to determine whether the dwelling is located in a potential flooding zone. Find out whether floods or high water have been observed in this area before, when exactly this happened and to what level the water rose. It is important to take into account the distance of the house to the bank of a river, lake or old woman. An additional danger is the location near a steep slope of a valley, ravine or a place where a ravine turns into a valley. To obtain accurate information, it is worth familiarising yourself with the ecological flood risk map (Fig. 8). At a scale of 1:10,000, it shows segments of a settlement that may be under water when it rises by 1, 2, 3... 10, 11, 12 meters. It is advisable for local authorities, together with surveyors, to mark these segments directly on the ground. It is also necessary to check the accessibility of roads and bridges in case of evacuation (Hnatushenko & Kashtan, 2021; Trigub & Domuschi, 2023; Wang *et al.*, 2024).

The results of the study predicted floods, which made it possible to create a three-dimensional model of the territories, which allows estimating the levels of flooding and determining environmental risks. Using GIS technologies, such as MapInfo Pro, researchers create interpolated surfaces, build contours and generate flood risk maps. For this, interpolation methods are used, in particular, the inverse distance weighted (IDW) method and irregular triangle network (TIN). The IDW method provides high modeling accuracy, especially for large amounts of data (Myrontsov, 2020; Moss *et al.*, 2020).

In the dissertation work of M.K. Halochkin (2022) reviewed the theoretical principles and methods of hydrological modeling of flood zones using remote sensing materials and geographic information systems. The main attention was paid to the analysis of changes in channel processes, the classification of flood modeling models, the use of Saint-Venant equations, as well as experimental studies on individual sections of the Dniester. An important component is the use of UAVs, Landsat and Sentinel satellite data, as well as the use of HEC-RAS software. However, it should be noted that the use of satellite data and geographic information systems in it has long been an established practice in the industry. The novelty of the research approach lies not only in the application of these technologies, but in the development of a universal methodology that allows you to quickly import geographic information models built in the MapInfo environment into any other GIS environment for further analysis, adaptation and decision-making. This provides high flexibility, scalability and compatibility of the project with modern spatial analysis systems.

In addition, the proposed system integrates methods of satellite monitoring, real-time processing and visualisation of results, which allows for prompt information of

local communities, increase their level of flood preparedness and reduce socio-economic consequences. Thus, the author's approach combines the advantages of classical solutions with modern requirements for adaptive risk management in the context of climate change. In contrast to the mentioned work, the author's research methodology offers a comprehensive approach to the integration of satellite monitoring and flood risk forecasting in the context of climate change. In particular, the emphasis is on the use of the latest technologies, such as the Sentinel-1 and Sentinel-2 satellite services for prompt detection of changes in the water table, as well as 3D modeling of flood processes using modern geoinformation software (MapInfo, QGIS, ArcGIS). Dynamic forecasts mean the ability of the model to be promptly updated based on new satellite and hydro-meteorological data. This allows for a flexible assessment of the risk of flooding taking into account changes in weather conditions in real time or close to it. In addition to risk mapping, researchers have proposed a methodology for developing practices for the first time.

Geographic information systems remain a component for flood risk analysis in urban settings, as demonstrated in the study by other researchers such as J. Balch *et al.* (2020) on the case of the city of Midar in Morocco. This study focuses on the significant role of GIS not only as a mapping tool but also as a key element in urban planning and management. Extremely careful identification and mapping of areas at risk of damage and flooding will provide a deeper understanding of the vulnerability of urban landscapes. The practical utility of GIS in reducing material losses is particularly relevant for areas with increased flood risk. The analytical framework presented in this study provides several important conclusions on the effectiveness of GIS in urban management. Also, the approach focuses on the protection of the population and infrastructure of Midar, demonstrating the potential for adaptation. Overall, the study highlights the transformative potential of GIS in increasing resilience, making this technology a key tool in the fight against natural disasters.

✓ Conclusions

As a result of the study, the feasibility of using a geoinformation approach to forecast flood risks within the Dniester flood control area was comprehensively substantiated. Climate change, in particular the increase in the intensity of atmospheric precipitation, as well as anthropogenic factors such as irrational water use, deforestation and urbanisation, significantly affect the hydrological regime of the region. This necessitates the creation of effective tools for monitoring, forecasting and responding to flood situations in order to ensure environmental safety and protect the population. For the first time, a comprehensive spatial model was created for the territory of the Dniester Valley and the adjacent regions of Podillia and Prykarpattia, combining data from remote sensing, geomorphological analysis and historical observations. Detailed mapping of Quaternary deposits, landscape structure and elevation levels of the relief was

carried out, which made it possible to identify patterns in the formation of flood waters and create a forecast map of flooding at different water levels. A particularly significant result was the construction of a 3D map of the territory in the GIS environment, which served as the basis for modeling flooding using the inverse-weighted distance method. This method turned out to be optimal for assessing the spatial distribution of risk in conditions of uneven location of hydrological posts.

The study of historical sources, including chronicles, chronicles and meteorological observation data, made it possible to identify the cyclical nature of the occurrence of catastrophic floods. It was established that floods have a clear periodicity within 3-4, 5-6 and 15-20 years, which corresponds to different phases of recurrence of extreme hydroclimatic phenomena. These data became the basis for the formation of a forecasting system capable of taking into account not only modern instrumental observations, but also long-term historical dynamics. An important practical achievement of the work was the creation of an automated information and measurement anti-flood system AVIPS-DNISTER, which combines cartographic, mathematical and geoinformation models. The system allows not only to model possible scenarios of the development of a flood situation, but also ensures the functioning of prompt notification of the population and relevant civil protection services in case of a threat of flooding. The proposed model for predicting water rise allows determining the level of danger for each specific settlement, depending on the morphology of the territory and the degree of vulnerability of the infrastructure.

The results of the study demonstrated the effectiveness of combining GIS analysis, remote sensing, and historical climate analysis methods for flood risk assessment. The proposed approach is universal and can be adapted for other regions of Ukraine and Central and Eastern Europe with complex terrain and flood threat. The practical implementation of the flood monitoring and forecasting system within the Dniester flood control area opens up new opportunities for sustainable water resource management, minimising the consequences of emergencies, and preserving the ecological balance in one of the most important natural regions of Ukraine. Thus, the study made a significant contribution to the development of environmental safety and natural risk management within the Dniester Valley, proposing a scientifically sound and technologically implemented flood forecasting model that has high social, economic, and environmental significance. To increase the effectiveness of the proposed approach, it is advisable to expand the use of quantitative analysis methods, including machine learning, as well as to introduce interdisciplinary cooperation to improve the flood monitoring and forecasting system.

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✓ Conflict of Interest

None.

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Інтеграція супутникового моніторингу для прогнозування паводкових ризиків на прикладі Дністровського протипаводкового полігону

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✓ **Анотація.** Актуальність дослідження полягає в розробці, вдосконаленні та практичному впровадженні геоінформаційного підходу до прогнозування паводкових ризиків у межах Дністровського протипаводкового полігону шляхом інтеграції супутникового моніторингу, просторового аналізу та інтерполяційних методів. Дослідження було спрямоване на створення ефективної системи виявлення потенційно небезпечних зон, аналізу забруднення паводкових вод та оцінки впливу кліматичних змін на гідрометеорологічні процеси з метою підвищення екологічної безпеки та забезпечення сталого управління ризиками на рівні територіальних громад. Виконано картографування четвертинних відкладів, геоморфологічних рівнів і ландшафтної структури, а також побудовано прогнозу карту затоплення територій за підйому води на 1, 3, 5 і 10-12 метрів. Остаточним результатом стала 3D-карта, яка представлена як інтерпольована поверхня, створена з використанням методу зворотних зважених відстаней. Підібрано оптимальні інтервали значення і розміру осередків: отриманий результат дозволяє не тільки аналізувати ризики затоплення, але й оформлювати звіти з візуалізацією даних, які зберігаються у вигляді графічних зображень. Уперше для Дністровської долини та суміжних територій Поділля й Прикарпаття була створена карта екологічного ризику затоплення Дністровського протипаводкового полігону катастрофічними паводками. Дослідження показало, що процес затоплення долини Дністра відбувається послідовно: спочатку затоплюється низька заплава (підйом води +1 м), потім середня (+3 м), висока (+5 м) заплава і, нарешті, перша надзаплавна тераса (+10-12 м). На основі виявлених закономірностей було розроблено систему прогнозування підйому вод під час паводків. Окрім прогнозування, ця система виконує функцію оповіщення населення про катастрофічні прояви водних стихій

✓ **Ключові слова:** інтерполяція; моделювання; дистанційне зондування; геоінформаційні системи; управління водними ресурсами



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; Vyshnevskiy, 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. Nezbryska *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. Khilchevskiy *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 (Khaitetsky, 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 investigation 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.

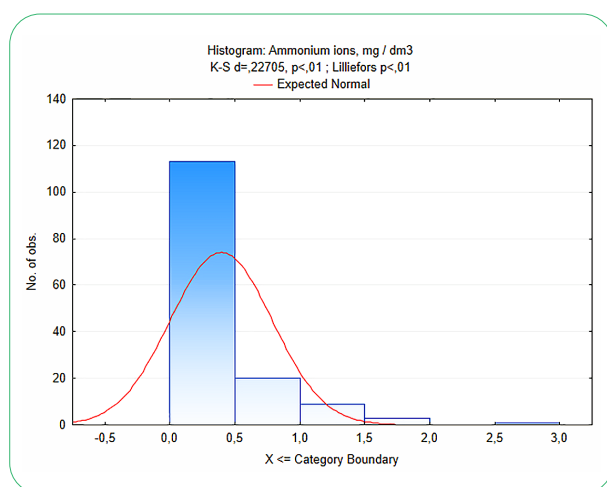


Figure 1. Histogram for ammonium ions, mg/dm³

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/dm³) 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/dm³, 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/dm³) 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.

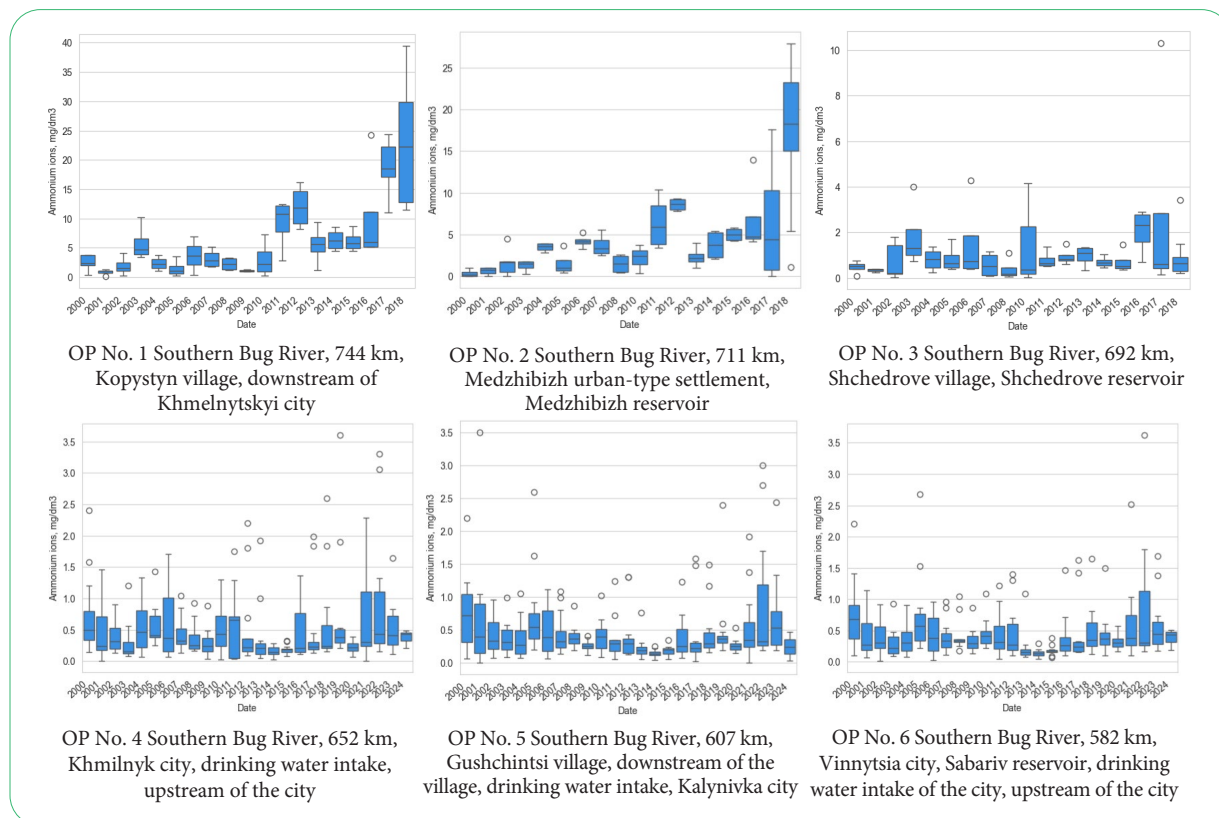


Figure 2. Span diagrams for the ammonium ions indicator in the upper reaches of the Southern Bug River
Source: created by the State Agency of Water Resources of Ukraine (2025)

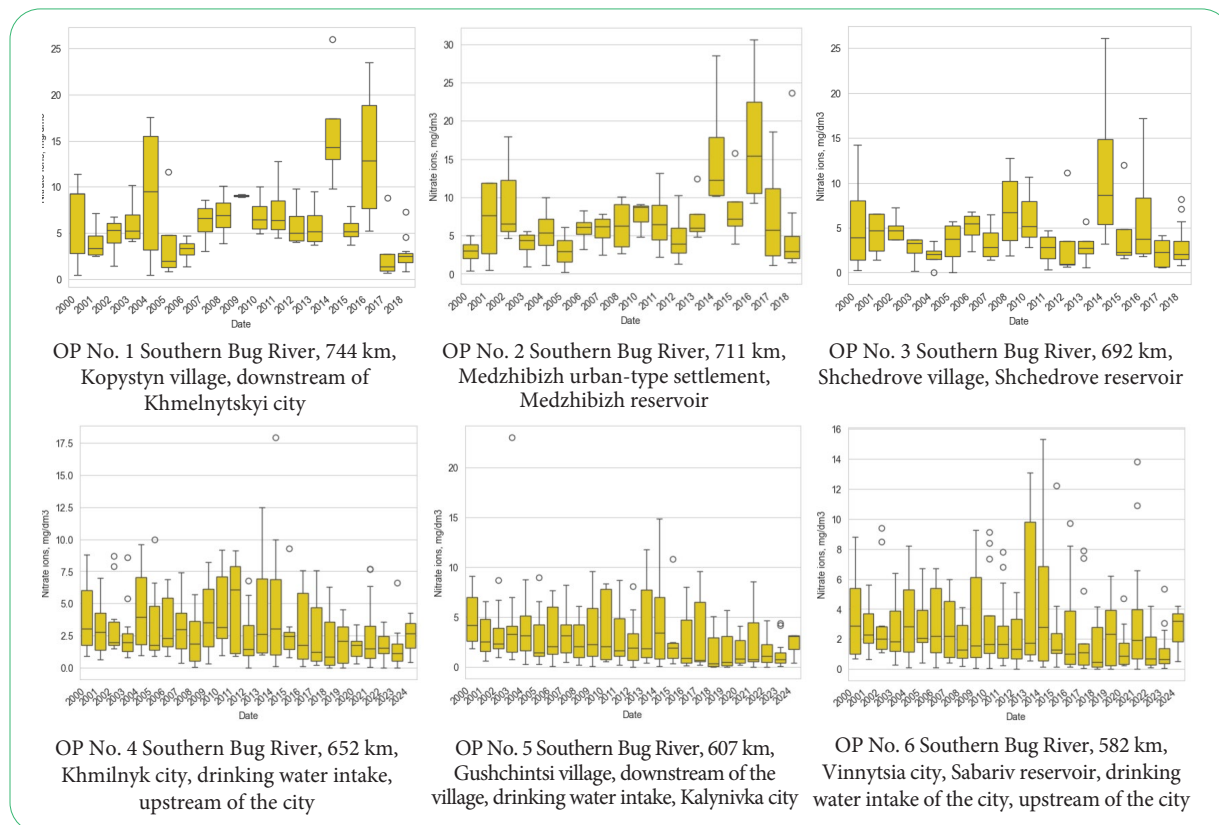


Figure 3. Span diagrams for the nitrate ion indicator in the upper reaches of the Southern Bug River
Source: created by the State Agency of Water Resources of Ukraine (2025)

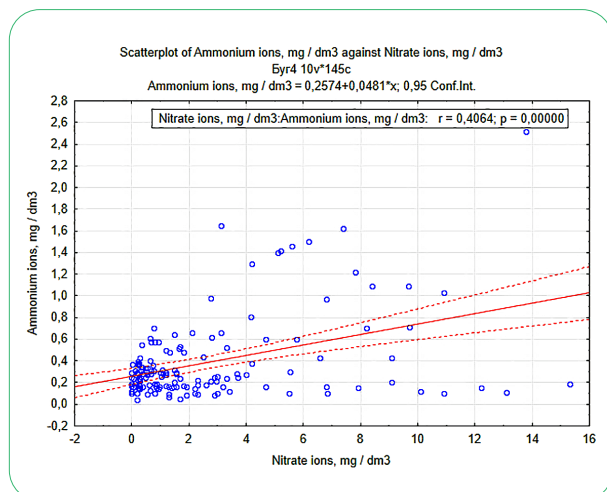


Figure 4. Scatter plot for ammonium ion and nitrate ion data from 2010 to 2022

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).

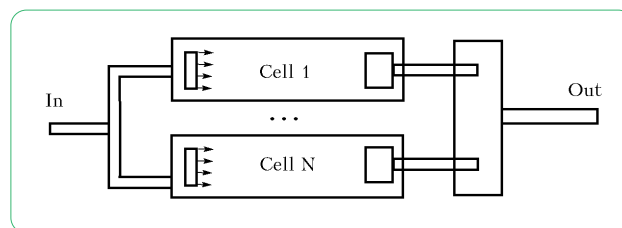


Figure 5. Diagram of a constructed wetland with a free water surface

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).

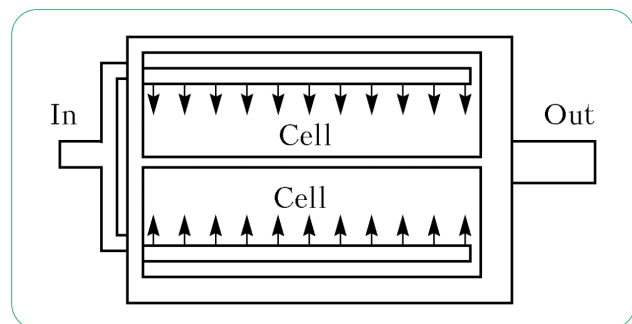


Figure 6. Diagram of a constructed wetland of a subsurface flow

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), evaporation, 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, microorganisms, 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 нітрогеновмісними сполуками та проаналізувати використання штучних водно-болотних угідь для запобігання цього забруднення. Було проведено статистичну обробку результатів вимірювань нітрогеновмісних 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 нітрогеновмісними сполуками, зокрема, нижче м. Хмельницький. За рахунок процесів самоочищення, що відбуваються у річці показники рівнів нітрогеновмісних 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 нітрогеновмісними 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

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