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The impact of temporary occupation and hostilities on the water conditions of the North Crimean and Kakhovka Main Canals

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✓ **Abstract.** The aim was to analyse the dynamics of water resources of the North Crimean and Kakhovka canals from 2013 to 2024 using remote sensing methods. The study utilised satellite imagery from Landsat 8 OLI/TIRS L2 (2013-2015) and Sentinel-2 L1C (2016-2024). The deep learning model "Water Body Extraction (SAR) – USA" based on Sentinel-1 C band SAR GRD VH data was applied. The normalised difference water index was used to detect water surfaces. Manual digitisation of the canals was performed based on time composites of satellite images over the study period. The analysis revealed significant changes in the water conditions of the canals due to natural and anthropogenic factors. Following the annexation of Crimea in 2014, the cessation of water supply from the Dnipro River led to the drying of canals on the peninsula, negatively affecting agriculture and ecosystems through soil salinisation and degradation. In 2015, the length of canals with water in Crimea decreased to 161.65 km. Alternative sources, such as artesian wells, partially compensated for the lack of water but led to groundwater depletion. From 2016 to 2021, the length of canals with water in Crimea continued to decrease, reaching 150.17 km in 2020. In 2022, after the destruction of dams in the Kherson Region, uncontrolled filling of canals with water occurred. Due to infrastructure degradation, a significant portion of water infiltrated into the ground, causing water losses. In 2023, the destruction of the Kakhovka Hydroelectric Power Plant dam led to the shallowing of the Kakhovka Reservoir and changes in the hydrological regime of the canals, reducing the length of canals with water in the Kherson Region to 448.41 km, and in 2024 to 298.98 km. These events caused erosion and lowering of groundwater levels, negatively affecting agriculture due to reduced irrigated areas

✓ **Keywords:** dynamics; irrigation; deep learning; spatial analysis; remote sensing; water security

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Introduction

In regions with a continental climate characterised by irregular and insufficient precipitation, canals are important not only for the agricultural sector but also for meeting the needs of the local population. Climate change, particularly rising temperatures and decreasing amounts of precipitation, leads to a reduction in the volume of water resources, which is acutely felt in the arid and semi-arid zones of the Ukraine's south. The shortage of fresh water is one of the biggest problems in the territories of the Autonomous Republic of Crimea, Kherson, and Zaporizhzhia regions. Thousands of square kilometres of land require irrigation, which is provided through a branched network of canals such as the North Crimean and the Kakhovka Main Canal. These canals play an important role in ensuring high crop yields and stable water supply. A stable water level in the irrigation system is a critically important aspect for ensuring water resources and maintaining ecological balance in any region. Scientists from various countries are working on improving methods for identifying water bodies and monitoring their changes.

T.V. Bijeesh & K.N. Narasimhamurthy (2020) analysed various methods for detecting water bodies, such as spectral indices, machine learning, and spectral mixture analysis. They concluded that spectral indices are less effective than deep learning models, which better adapt to data but require more resources. To improve the accuracy of water identification, they recommended combining different methods and using synthetic-aperture radar (SAR) and panchromatic images. F. Chen *et al.* (2020) proposed a new method for identifying water bodies in urban areas. Unlike traditional spectral indices that use only two bands (normalised difference water index (NDWI), modified normalised difference water index (MNDWI)), their method uses multiple bands and analyses the interrelationship between visible bands, near-infrared (NIR) and short-wave infrared (SWIR) bands. It increases the accuracy of water identification by relying on the observation that water has a lower reflectance coefficient in the NIR and SWIR ranges and absorbs radiation in the SWIR range. X. Deng *et al.* (2020) used remote sensing to track annual and seasonal changes in water levels in reservoirs of the Yellow River. They determined that the most accurate approach integrates optical and radar images, as SAR images provide stable accuracy under any conditions, and optical images add details in clear weather. Implementing machine learning algorithms can further improve accuracy, especially for detailed classification.

O. Vlasova *et al.* (2023) monitored water bodies and reclaimed lands affected by hostilities, using the example of flooding of the floodplains of the Irpin and Dnipro rivers. They used spectral indices and series of Landsat 8 and Sentinel-2 L2A satellite images to analyse changes in land cover. The method allows for the rapid diagnosis of flooded areas, determining flood extents, and predicting the impact on reclaimed lands. In the study by G. Wang *et al.* (2020), convolutional neural networks (CNN) and the NDWI spectral index were applied to identify water in the area of

Lake Poyang. They found that DenseNet performs much better than other CNNs and the NDWI method, considering the accuracy of identification results. H. Guo *et al.* (2020) proposed a new convolutional neural network for semantic segmentation, multi-scale water extraction convolutional neural network (MWEN), for automatic extraction of water bodies from GaoFen-1 (GF-1) remote sensing images. In the article by W. Jiang *et al.* (2021), a new approach to detecting water bodies was proposed using an improved water index for Sentinel-2 images – the Sentinel-2 water index (SWI). The authors developed and evaluated a new water index that demonstrates improved accuracy in water detection compared to traditional indices like NDWI. E. Özelkan (2020) explored the effectiveness of using the spectral index of three NDWI models: NDWI (Green, NIR), NDWI (Green, SWIR1), and NDWI (Green, SWIR2) for detecting water bodies on Landsat-8 OLI images. S. Liu *et al.* (2023) conducted a comparative analysis of 10 spectral indices calculated on Landsat TM/OLI images used for extracting surface water bodies.

The water supply situation in the territory of the Autonomous Republic of Crimea became especially difficult after the annexation of the peninsula in 2014 and, as a result, the closure of the channel of the North Crimean Canal in the southern part of the Kherson Region, which significantly complicated the provision of water to the peninsula. With the start of the full-scale invasion of the Russian Federation into the territory of Ukraine in 2022, dams in the Kherson Region that blocked the channel of the North Crimean Canal were destroyed, resulting in uncontrolled filling with water of part of the North Crimean Canal, whose channel had degraded since annexation. A significant part of the water from the Dnipro infiltrated into groundwater horizons, leading to substantial water losses. Under such conditions, the issue of determining and forecasting the dynamics of water in river channels has acquired a new level of relevance. Therefore, the aim was to analyse the dynamics of water resources of these canals from 2013 to 2024, to identify factors influencing their condition, and to propose ways to restore irrigation systems.

Materials and Methods

Description of the research area. The North Crimean and Kakhovka Main Canals are located in three regions of Ukraine: the Autonomous Republic of Crimea, Kherson, and Zaporizhzhia regions. The area where the canals are located has a moderately continental climate characterised by significant seasonal temperature fluctuations and uneven distribution of precipitation throughout the year, ranging from 350-500 mm. The unstable level of precipitation leads to droughts, affecting agricultural practices and causing a shortage of water resources. The total length of the North Crimean and Kakhovka Main Canals along with their branches is 1,219.64 km in the Kherson Region, 171.23 km in Zaporizhzhia, and 2,177.55 km in the Autonomous Republic of Crimea (Fig. 1).

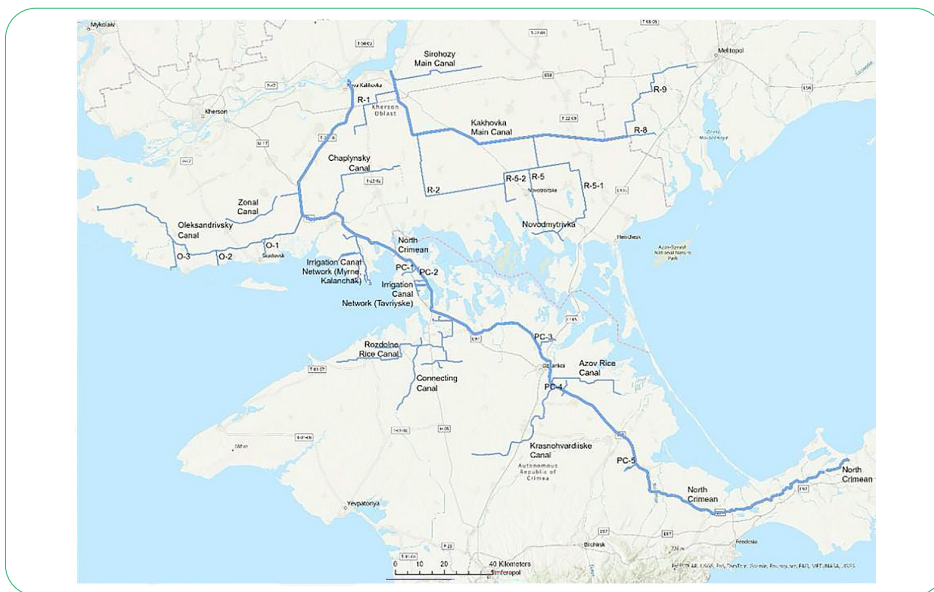


Figure 1. Map-scheme of the location of the North Crimean and Kakhovka Main canals

Source: created by the authors

The North Crimean Canal is a hydraulic engineering structure that, until 2014, provided water for irrigation to approximately 400,000 hectares of agricultural land and covered about 85% of the peninsula's water supply needs. The canal begins from the Kakhovka Reservoir, near the city of Tavriisk, and stretches south through the Black Sea Lowland and the Perekop Isthmus to Crimea. The total length of the North Crimean Main Canal is 402.6 km. The width of the canal varies from 110-120 m (up to the Krasnoznamenetsky Canal) to 25-30 m (near Dzhankoi), and the average depth is 4.6 m. The maximum capacity of the canal is 380 m³/s. On average, about 1.5-2 km³ of water flowed through the canal per year, ensuring the maintenance of ecosystems and water supply for 1.9-2.1 million people in Crimea (Mankovska, 2021). The main branches that depart from the North Crimean Canal include the Krasnoznamenetsky and Chaplynsky canals in the Kherson Region, and the Rozdolnenska branch, Chervonogvardeiska branch, and Azov Rice Canal in Crimea.

The Kakhovka Main Canal is located mainly in the Kherson Region. The primary purpose of the canal is to irrigate agricultural lands covering an area of 216,000 hectares (190,100 ha in Kherson and 25,900 ha in Zaporizhzhia regions) and to supply water to the cities of Melitopol, Berdiansk, and 27 rural settlements in Kherson and Zaporizhzhia regions. The Kakhovka Main Canal has a total length of about 130 km. The width of the canal varies but averages from 10 to 20 m. The depth of the canal, depending on the section and season, is up to 10 m (A unique..., n.d.). From the Kakhovka Main Canal originate the Pryazov, Sirogoz, Henichesk, Kalanchak, and Perekop irrigation systems.

Methodology and its selection. The paper has employed a number of remote sensing methods for analysing water resources, particularly for monitoring the dynamics

of the water cover of the North Crimean and Kakhovka canals. The main methods used in the study include comparison, measurement, change analysis, interpolation, extrapolation, geostatistics, linear regression, spectral indices, and deep learning methods. The comparison method involved comparing different datasets or images obtained at different times or from different sources. The measurement method was applied to obtain the lengths of canals with identified water. The analysis method was used to detect changes in the water conditions of canals over different years.

For the analysis and assessment of the water conditions of the canals in Southern Ukraine, images from Landsat 8 OLI/TIRS L2 satellites (for 2013-2015) with a spatial resolution of 30 m (USGS, n.d.), Sentinel-2 L1C (for 2016-2024) with a spatial resolution of 10 m, and Sentinel-1 C band SAR GRD VH with a spatial resolution of 10 m (Copernicus..., n.d.) were used. Open-source data from catalogued state and international sources included layers from OpenStreetMap (n.d.), Sentinel-2 Land Cover Explorer (n.d.) water cover obtained based on Sentinel-2 L2A images with a spatial resolution of 10 m, and OCHA Services (administrative boundaries of Ukraine level 1 – regions) (Ukraine..., n.d.).

For automatic identification of canals in the territories of Kherson and Zaporizhzhia regions, and the Autonomous Republic of Crimea, the deep learning model "Water Body Extraction (SAR) – USA" (2022) was used. This model employs SAR data to determine water surfaces based on processing radio images obtained from SAR satellites. The model classifies the pixels of the input raster and assigns them a class identifier. Pixel classification was carried out on the input 3-band composite raster Sentinel-1 C band SAR GRD VH with parameters: padding – 128, batch size – 4. This is because the number of image fragments processed

at each step of the model's operation (batch size) depends on the video card's memory and only affects the processing time, and padding is a parameter that determines the size

of the overlap of image fragments, with a maximum value of 256 for this model. However, the model proved insufficiently effective for extracting irrigation systems (Fig. 2).

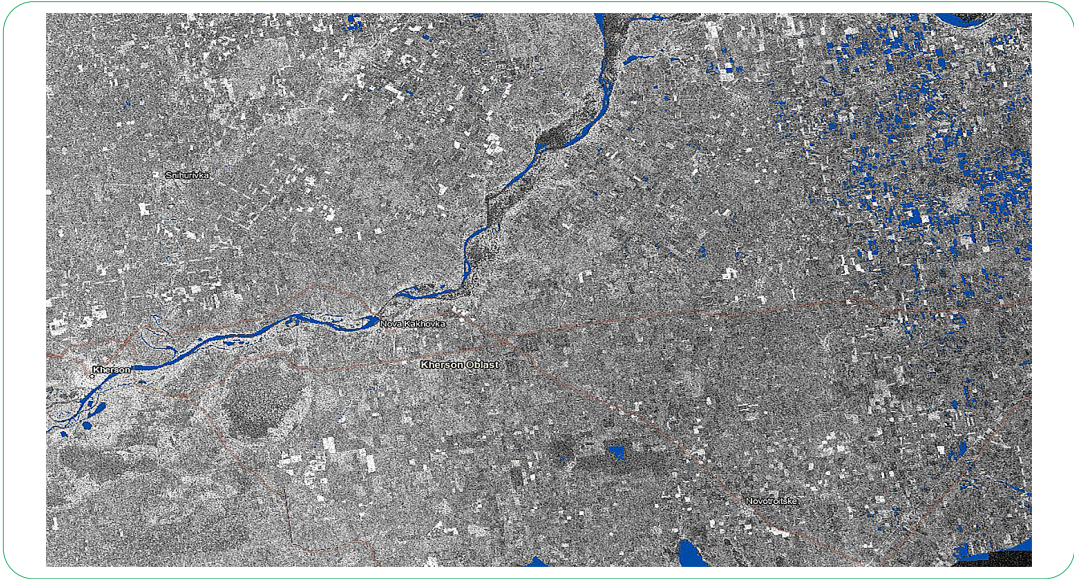


Figure 2. Identified water resulting from the operation of the water body extraction model on a part of the Kherson Region

Source: created by the authors

Therefore, an attempt was made to improve the results by retraining the model. Considering the specifics of the land cover types and the width of the irrigation system objects, a training sample was created with parameters: image format – TIFF, tile size X, Y – 512, metadata format –

Classified Tiles (Fig. 3). Despite retraining, water objects in the image were not fully identified. The model mainly detected objects like rivers and reservoirs because most irrigation canals have a small width, complicating their recognition on images with a spatial resolution of 10 m.



Figure 3. Training sample for retraining the water body extraction model

Source: created by the authors

The Esri Sentinel-2 Land Cover Explorer (n.d.) resource was then also considered, where global land cover is identified and classified based on Sentinel-2 satellite images with a resolution of 10 m using the Impact Observatory deep learning model into nine types, including water resources. However, identifying water in canals,

especially their smaller branches, was a more complex task for the model. Therefore, the model did not always identify water in the image that the human eye can distinguish. In the 2018 image, it is evident that the Perekop Canal is filled with water (Fig. 4a), but the water in the canal was not identified by the model (Fig. 4b).



Figure 4. Perekop Canal images

Note: a – canal with water in Sentinel-2 images, true colour composition; b – identified water in the canal according to Sentinel-2 Land Cover Explorer
Source: created by the authors

Using the EO Browser (n.d.) resource, the NDWI has been applied to monitor changes related to water content in water bodies. However, this method did not yield the desired results and did not identify water even in the largest canals. In Figure 5a, a part of the North Crimean Canal

is presented in a true colour composition based on Sentinel-2 satellite images. The image shows that the canal is filled with water. However, when the NDWI visualisation was applied to the same section of canal, the water was not identified (Fig. 5b).



Figure 5. North Crimean Canal in Sentinel-2 satellite images

Note: a – true colour composition; b – NDWI index composition
Source: created by the authors

Due to unsatisfactory model results and incomplete data from third-party resources, it was decided to supplement previous methods with the method of manual delineation of water levels in the canals. Delineation was carried out based on time composites of satellite images over a 12-year period from 2013 to 2024. Sentinel-2 satellite images have better spatial resolution than Landsat 8 images, but the Sentinel-2 mission was launched in 2015. Therefore, for the period from 2013 to 2015, Landsat 8 images were used, and from 2016 to 2024 – Sentinel-2 images. The imaging period was chosen based on the period of water supply to

the North Crimean Canal, approximately from March to May. However, considering the availability of images and their cloudiness, the period was extended to June for Sentinel-2 images and to August for Landsat 8 images.

✓ Results and Discussion

An analysis of satellite images from 2013 to 2024 allowed for the assessment of changes in the water conditions of canals in the southern regions of Ukraine due to factors such as climate change, variability of atmospheric precipitation, hostilities, and the impact of temporary

occupation. One of the main reasons for the change in the water conditions of the North Crimean Canal was the annexation of Crimea by Russia in 2014, which significantly affected the functioning of the canal that had previously supplied water from the Dnipro River to the peninsula. After the annexation, Ukraine ceased the supply of water to the North Crimean Canal; from April 2014 to March 2022, water from the Dnipro did not flow through the canal. Without water from the main source, the canal lost its functionality, leading to its drying up and negatively impacting agriculture and the state of the natural environment of the peninsula. The absence of water supply from the Dnipro caused ecological problems, including

secondary soil salinisation and degradation of steppe, water, and agro-ecosystems.

As of mid-2013, the total length of canal channels with water in the North Crimean and Kakhovka Main Canals, along with their branches, reached: in the Kherson Region 772.16 km, in the Zaporizhzhia Region 66.75 km, in the Autonomous Republic of Crimea 561.34 km (Fig. 6). In 2014, after the annexation of Crimea and the shutdown of the North Crimean Canal supply, the total length of channels with water in the North Crimean and Kakhovka Main Canals, along with their branches, was: in the Kherson Region 582.04 km, in the Zaporizhzhia Region 73.41 km, and in the Autonomous Republic of Crimea 389.60 km.

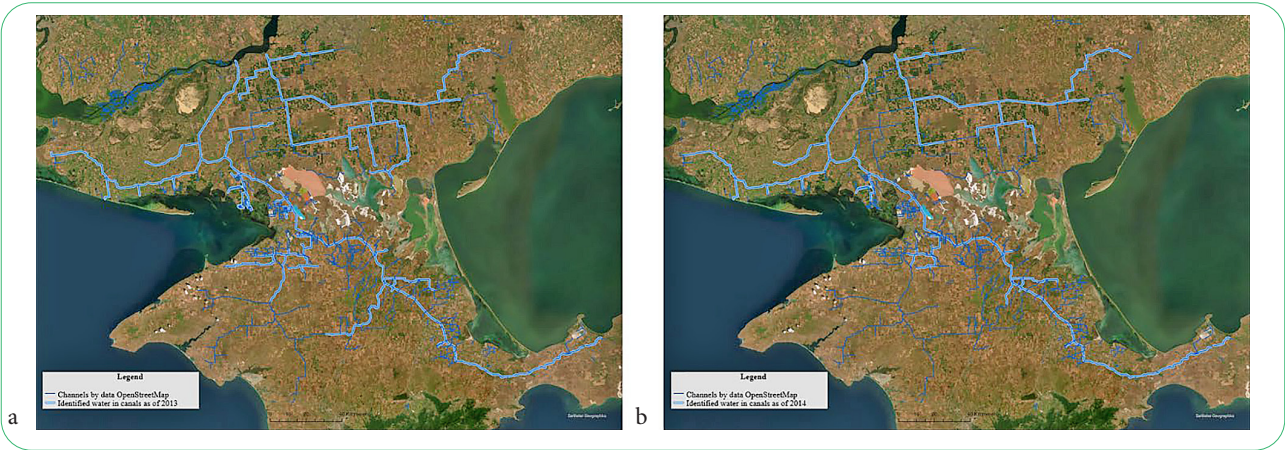


Figure 6. Identified water in canals, 2013-2014

Source: created by the authors

Since the North Crimean Canal stopped receiving water from the Kakhovka Reservoir, the water level in the Kakhovka Canal began to decrease. This happened because the portion of water that previously flowed into the canal for irrigation in Crimea was no longer used, and the water level in the canal started to fluctuate. This led to the need to rebalance water resources and changes in water use for irrigation and other needs. After the occupation of the peninsula in 2014, the volume of fresh water consumption decreased fivefold – to 310 million m³, with losses up to 16 million m³. The total volume of water intake in 2015 amounted to 253.46 million m³, including: 138.47 million m³ from fresh surface sources (55%); 95.13 million m³ from groundwater (37%); 19.86 million m³ of seawater (8%). Water losses amounted to 13 million m³ (about 6%). Of this volume, 50% was used for industrial needs, 39% for domestic and drinking needs, and 6% for irrigation (Hai-Nyzhnyk, 2017). Due to a decrease in the average annual precipitation to 300-350 mm in 2015, droughts were observed, which was one of the factors affecting the water conditions of the canals during this period. The total length of canal channels with water in the North Crimean and Kakhovka Main Canals, along with their branches, in 2015 was: in the Kherson Region 457.63 km, in the Zaporizhzhia Region 28.57 km, in the Autonomous Republic of Crimea 161.65 km (Fig. 7).

In Figure 7, it is evident that despite the cessation of Dnipro water supply to the North Crimean Canal, some of its sections still had water. Russia was forced to seek alternative water supply sources. Construction of new water intake facilities and infrastructure to meet the peninsula's needs began. However, these measures could not fully compensate for the loss of water from the North Crimean Canal. One such project was the extraction of groundwater from Crimea, which included the development of new artesian wells (Hai-Nyzhnyk, 2014). By extracting water from artesian wells, water was transferred along the canal bed to the eastern part of Crimea, in the area of Feodosia and surrounding territories. Figure 7 shows that from 2015 to 2022, there was water consistently in the bed of the North Crimean Canal. This allowed for partially compensating for the absence of water from the Dnipro and providing irrigation of lands and water supply for local needs. However, this method led to negative consequences, such as lowering groundwater levels, soil salinisation, and a decrease in the amount of water in rivers and reservoirs.

After the cessation of water supply, the North Crimean Canal effectively lost its functionality. Its infrastructure, including concrete reinforcements, dams, and locks, began to gradually deteriorate due to the lack of maintenance and natural factors. This included issues with erosion, pollution,

and a decline in the technical condition of canals and pumping stations. The total length of canal channels with water on the territory of Crimea gradually decreased from 2016, reaching minimal values in 2020. As of 2016, the total length of canal channels with water was: in the Kherson

Region 723.68 km, in the Zaporizhzhia Region 91.90 km, in the Autonomous Republic of Crimea 335.52 km. In 2020, the lengths of canals with water were: in the Kherson Region 643.79 km, in the Zaporizhzhia Region 88.02 km, in the Autonomous Republic of Crimea 150.17 km (Fig. 8).

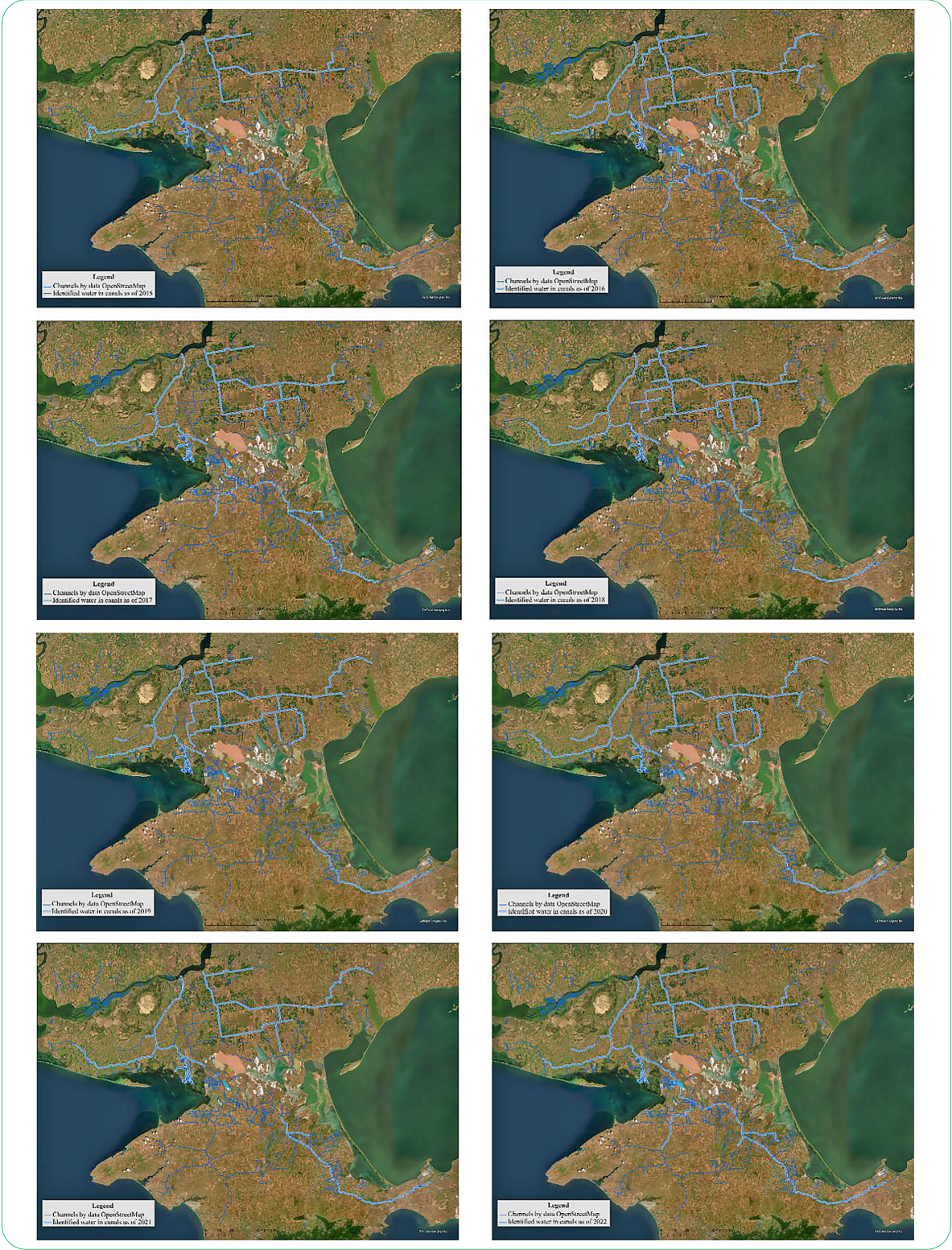


Figure 7. Identified water in canals, 2015–2022

Source: created by the authors

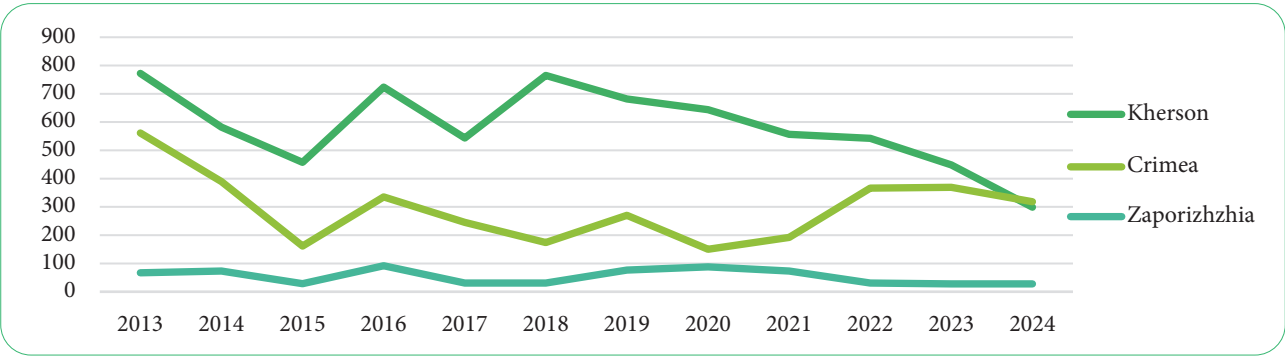


Figure 8. Graph of the dynamics of the total length of canals with identified water, 2015-2024, km
Source: created by the authors

The main reasons for the decrease in water level and reduction in canal lengths with water from 2015 to 2021 were the absence of Dnipro water supply and the depletion of alternative water sources. However, fluctuations in precipitation and periods of extremely high temperatures recorded in the summers of 2017, 2018, and 2020 affected the water conditions, leading to changes in water levels. Until 2022, the North Crimean Canal was used only partially for water transportation, mainly in the eastern part of Crimea. Its primary function as a water transport canal was lost. At the end of February 2022, a dam in the Kherson Region blocking water supply to the North Crimean Canal was destroyed. However, water began to reach Crimea in the second half of March after the demolition of a stationary hydraulic structure. After the destruction of the hydraulic unit, water began to flow uncontrollably, without adhering to necessary speed regimes. The unsatisfactory technical condition of the canal contributed to rapid infiltration of water into the soil and led to deformation of structures and faster wear of pumps. The release of water through the North Crimean Canal coincided with a period of intense atmospheric precipitation. As a result, the supply of water proved ineffective, as water resources were not optimally used for agricultural needs. Additionally, the destruction of the dam caused serious environmental problems, including

flooding of lands, which negatively impacted agriculture and natural ecosystems in the region (Kitowski *et al.*, 2023).

In 2022, the total length of channels with water was: Kherson Region 542.65 km, Zaporizhzhia Region 30.89 km, and Autonomous Republic of Crimea 366.70 km (Fig. 7). In June 2023, Russian forces destroyed the dam of the Kakhovka Hydroelectric Power Plant, causing a rapid shallowing of the Kakhovka Reservoir and flooding of the Dnipro's banks downstream (Vyshnevskiy *et al.*, 2023). The destruction led to massive water discharge, altering the hydrological regime of the canal and surrounding areas (Zgurovsky *et al.*, 2023). After the dam's destruction, the reservoir level dropped, stopping water inflow into the canal. The intensive water discharge provoked erosion of canal banks, water pollution, and changes in the regional ecosystem. Local flora and fauna suffered, and water quality issues arose. Rising water levels damaged pumping stations, hydraulic structures, and other infrastructure elements. In 2023, the total length of canal channels with water was: Kherson Region 448.41 km, Zaporizhzhia Region 27.73 km, and Autonomous Republic of Crimea 369.39 km (Fig. 9). In 2024, the total length of channels with water was: Kherson Region 298.98 km, Zaporizhzhia Region 27.73 km, and Autonomous Republic of Crimea 318.26 km (Fig. 10).



Figure 9. Identified water in canals, 2023
Source: created by the authors



Figure 10. Identified water in canals, 2024

Source: created by the authors

After the destruction of the Kakhovka Hydroelectric Power Plant, precipitation amounts and temperature fluctuations became the main factors affecting reservoir levels on the peninsula. Crimea’s moderate climate means any changes in precipitation can significantly impact

water availability. Rising temperatures may increase water evaporation, affecting reservoir levels. A similar situation occurred in 2020, when extremely high temperatures and insufficient precipitation caused drought and lowered reservoir levels (Table 1).

Table 1. Length of canal channels where water was identified, km

Area	2013	2016	2020	2024
Autonomous Republic of Crimea	561.34	335.52	150.17	318.26
Azov Rice Canal	36.51	30.78	13.65	28.70
Connecting Canal	30.96	26.77		
Krasnohvardiiskiy Canal	58.84			
Irrigation Canal Network (Tavriisk)	20.74	19.74	14.47	15.54
North Crimean Canal	256.53	234.55	117.81	245.97
PC-1	7.05		2.92	2.92
PC-2	1.31		1.31	1.31
PC-3	9.47			
PC-4	7.23			
PC-5	8.50			
Rozdolne Rice Canal	124.19	23.69		23.82
Zaporizhzhia	66.75	91.90	88.02	27.73
R-8	10.66	21.72	21.72	
R-8-1		14.09	3.55	
R-9	55.68	55.68	62.34	16.70
Kakhovka Main Canal	0.41	0.41	0.41	11.03
Kherson	772.16	723.68	643.79	298.98
R-1	33.61	28.94		
R-1-1				
R-2	58.41	58.41	38.58	38.99
R-2-1		25.11	25.13	
R-5	40.55	40.58	40.58	
R-5-1	54.17	54.17	54.16	
R-5-2	25.82	25.86	25.86	
R-8	1.27	1.34	1.34	
R-9	0.05	0.05	0.05	0.05
Zonal Canal	34.62	36.27	36.27	7.69
Kakhovka Main Canal	117.85	117.85	117.85	119.18
Irrigation Canal Network (Myrne, Kalanchak)	67.70	77.50	60.59	39.53
Novodmytrivka	14.85		12.26	
O-1	6.97			

Table 1. Continued

Area	2013	2016	2020	2024
O-2	5.97			
O-3	14.46			
Oleksandrivskyi Canal	104.61	51.82	81.04	
Perekopskyi Canal		55.25		
North Crimean Canal	110.22	110.22	109.76	93.54
Sirohozy Main Canal	38.50	40.33	40.33	
Chaplynskyi Canal	42.54			

Note: codes indicate the branches of the channels, see Figure 1

Source: created by the authors

The majority of water resources necessary for the peninsula are directed towards agriculture and production. In water deficit conditions, cultivating crops like rice, vegetables, and garden plants becomes impossible. This leads to a shift towards less demanding but low-profitability crops due to reduced yields without irrigation, potentially causing a gradual decline in agricultural production. Since other water sources in Crimea are insufficient, utilising underground wells becomes a possible option for agriculture. Over the past 10 years, transporting artesian water via branches of the North Crimean Canal to eastern Crimea has been practiced. However, using this resource negatively affects both the soils irrigated and the underground sources themselves. Depleting groundwater reserves, especially for agricultural needs, will lead to the loss of this source for many decades. Additionally, changes in groundwater levels can harm regional ecosystems. Lower groundwater levels may increase salt concentrations due to infiltration of brackish water from the Black and Azov Seas, affecting water quality and availability for the population.

To ensure sustainable water supply and restore the region's agricultural potential, it is necessary to do the following. The canal infrastructure needs to be restored by repairing and modernising hydraulic structures, dams, and pumping stations to control water levels and prevent losses caused by infiltration and damage. Effective water management methods should be implemented by utilising modern technologies for monitoring and forecasting canal water levels, as well as distributing water resources efficiently among consumers. Climate adaptation strategies must also be developed, considering projected climate scenarios in water supply and irrigation planning, and introducing drought-resistant crops. Ensuring environmental safety is crucial, which involves implementing protective measures to prevent soil salinisation and water pollution. The international cooperation should be strengthened, engaging international organisations and experts to exchange experiences and resources in water management and the restoration of affected areas. Joint efforts at local, national, and international levels can overcome these challenges and ensure the region's sustainable development.

Research on the dynamics of water resources using remote sensing methods is extremely relevant due to the growing need for monitoring water systems. Under martial

law conditions, commercial high-resolution images of the territory of Ukraine are not publicly available and are often inaccessible to scientific institutions even on a commercial basis for security reasons. Therefore, studying this problem can only be conducted based on open sources, which significantly complicates monitoring. Images available in open access have medium resolution, which does not provide sufficient accuracy for identifying small water bodies such as small irrigation canals. The results of the research showed significant changes in the water level of the North Crimean and Kakhovka Main Canals as a result of the temporary occupation and hostilities. These changes affected not only the water supply of the region, but also the ecological condition and agricultural activity.

Comparing obtained results with other studies, both commonalities and differences in conclusions and approaches were detected. S. Velychko & O. Dupliak (2023) studied the impact of the full-scale aggression on water bodies as sources of water supply. It was emphasised that the conduct of hostilities has a direct impact on the state of water bodies due to the destruction of water intake structures and the contamination of water with chemical substances. Obtained results confirm these conclusions, especially regarding the destruction of hydrotechnical structures in the Kherson Region and the uncontrolled inflow of water into the North Crimean Canal after the detonation of the dams.

O. Shumilova *et al.* (2023), in their analysis of the impact of the Russian-Ukrainian armed conflict on water resources, indicated multiple negative consequences for the availability and quality of fresh water for the civilian population. Threats to water infrastructure and ecosystems were identified. Paper's findings are consistent with their ones, especially regarding the risks to public water supply and agriculture from infrastructure destruction. V. Stokal & A. Kovpak (2022) emphasised military actions that negatively affected the state of water bodies and can lead to disruption of processes in water ecosystems. They noted that the destruction of water infrastructure and water pollution by heavy metals are the main consequences. Provided research confirms these aspects, in particular, regarding the pollution of water bodies due to the conduct of hostilities and the destruction of hydrotechnical structures.

A. Zubko (2022) conducted an analysis of the water-related dimensions of Russian aggression in Southern Ukraine,

emphasising the critical role of water as a strategic factor in the conflict. The study highlights the strategic importance of controlling water resources, aligning with the current study conclusion that the occupation of the North Crimean Canal served not only military objectives but also economic and environmental purposes. T. Khaing & T.P.L. Nguyen (2022) examined water management in the context of armed conflict in Rakhine State, Myanmar, concluding that such conflicts exacerbate challenges in managing water resources and necessitate adaptive strategies that incorporate local community participation. While their study focused on a different region, the authors concur that conflict-driven approaches to water management must be re-evaluated, emphasising the involvement of local communities and the adaptation of strategies to evolving circumstances.

O. Zemlianska *et al.* (2023) evaluated the environmental damage to Ukraine's water resources caused by Russia's military aggression, emphasising the long-term consequences of water body pollution, infrastructure destruction, and other adverse effects on the environment and public health. The findings of this study verify these conclusions, particularly in relation to soil salinisation, ecosystem degradation, and the health risks associated with deteriorating water quality. In contrast to some experts, e.g., O. Vasyliuk & E. Simonov (2024), who proposed groundwater extraction as a sustainable long-term solution, the authors assume that it may have negative environmental consequences and is not a sustainable solution.

Based on the analysis of the above studies, several key conclusions can be drawn. Comprehensive approach to restoration: consistent with the findings of O. Shumilova *et al.* (2023), the continuation of the conflict will have negative consequences not only at the national level, but also at the global level. Therefore, a comprehensive approach to the restoration of water infrastructure is necessary, taking into account ecological, social and economic aspects. Involvement of local communities: as noted by T. Khaing & T.P.L. Nguyen (2022), the participation of local communities in water management is critical. This will help to adapt management strategies to the real needs and conditions of the region. Monitoring and assessment of environmental damage: O. Zemlianska *et al.* (2023) emphasised the importance of systematic monitoring and analysis of the consequences of military aggression. The authors support this perspective, as it is necessary to develop algorithms for assessing losses and mechanisms for minimising economic losses. Restoration of irrigation systems: given the importance of irrigation for agriculture, restoration and modernisation of irrigation systems to ensure food security should be a priority.

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Conclusions

The study results demonstrated the significant impact of temporary occupation and hostilities on the water conditions of the North Crimean and Kakhovka Main Canals. Analysis of satellite images from 2013 to 2024 revealed substantial changes in the lengths of water-filled canal channels, directly correlating with geopolitical events and military conflicts in the region. The annexation of Crimea in 2014 led to the cessation of Dnipro water supply through the North Crimean Canal, causing a sharp decrease in water availability and negatively impacting agriculture and the ecological state of Crimea and the Kherson Region. The total length of channels with water decreased from 561.34 km in 2013 to 389.60 km in 2014. The shallowing and drying up of the canal's branches led to degradation of agricultural lands, reduced yields, and deterioration of the region's ecological state. To compensate for the absence of Dnipro water, alternative sources like groundwater were developed. However, these measures could not meet regional needs and led to aquifer depletion and soil salinisation.

Following the full-scale invasion in 2022, dams in the Kherson Region were destroyed to fill the North Crimean Canal – the canal's water-filled length increased from 192.02 km in 2021 to 366.70 km in 2022. However, uncontrolled water inflow led to flooding, bank erosion, and infrastructure damage, negatively affecting ecosystems, water quality, and posing threats to the local population and agriculture. Climate change, particularly rising temperatures and uneven precipitation distribution, further complicates water supply in Ukraine's southern regions. Increased temperatures boost evaporation rates, reducing available water resources and intensifying arid conditions. Further research in this area is critically important for understanding the long-term consequences of occupation and military actions on the region's water resources. A comprehensive approach to solving canal water issues will aid in restoring the economic potential of Ukraine's southern regions and improving the quality of life for the local population.

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Conflict of Interest

None.

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Вплив тимчасової окупації та бойових дій на водний стан Північно-Кримського та Каховського магістральних каналів

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✓ **Анотація.** Мета роботи полягала в дослідженні динаміки водних ресурсів Північно-Кримського та Каховського каналів із 2013 по 2024 роки за допомогою методів дистанційного зондування. У дослідженні використано супутникові знімки Landsat 8 OLI/TIRS L2 (2013-2015) та Sentinel-2 L1C (2016-2024). Застосовано модель глибинного навчання «Water Body Extraction (SAR) – USA» на основі даних Sentinel-1 C band SAR GRD VH. Використано нормований різницевий водний індекс для виявлення водних поверхонь. Виконано ручне оцифрування каналів на основі часових композитів супутникових знімків за досліджуваний період. Аналіз супутникових знімків показав суттєві зміни у водних умовах каналів через природні та антропогенні фактори. Після анексії Криму у 2014 році припинення постачання води з Дніпра призвело до висихання каналів на півострові, негативно вплинувши на сільське господарство та екосистеми через засолення та деградацію ґрунтів. У 2015 році довжина каналів із водою в Криму зменшилася до 161,65 км. Альтернативні джерела, такі як артезіанські свердловини, частково компенсували відсутність води, але призвели до виснаження підземних вод. З 2016 по 2021 рік довжина каналів із водою в Криму продовжувала зменшуватися, досягнувши 150,17 км у 2020 році. У 2022 році, після руйнування дамб у Херсонській області, відбулося неконтрольоване заповнення каналів водою. Через деградацію інфраструктури значна частина води інфільтрувалася у ґрунт, спричиняючи втрати водних ресурсів. У 2023 році руйнування дамби Каховської ГЕС призвело до обміління Каховського водосховища та змін у гідрологічному режимі каналів, зменшивши довжину каналів із водою у Херсонській області до 448,41 км, а у 2024 році до 298,98 км. Ці події спричинили ерозію берегів та зниження рівня підземних вод, що негативно вплинуло на сільське господарство через зменшення зрошуваних площ

✓ **Ключові слова:** динаміка; зрошення; глибинне навчання; просторовий аналіз; дистанційне зондування; водна безпека



Modelling infiltration processes in rain gardens: Influence of design parameters on hydrological efficiency

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✓ **Abstract.** A rain garden is a stormwater management system designed for on-site water control. Suboptimal rain garden designs may compromise hydrological performance during operation, necessitating developing and validating a mathematical model for engineering calculations and design assessment. This study aimed to model infiltration processes in a rain garden using a mathematical framework that accounts for the height of the water column (HWC) on the surface and the filtration coefficient of soil materials, simulating system behaviour during an extreme rainfall event (36 mm/h). The developed model generated performance curves illustrating the rain garden's efficiency as a function of design parameters: construction depth, catchment-to-garden area ratio, filtration coefficient, and water retention capacity (WRC). Key soil material parameters were determined experimentally under laboratory conditions. The infiltration performance of the system was evaluated by analysing the variation in infiltration time, saturation of all layers, and the water filling level of the rain garden resulting from adjustments to its parameters and changes in HWC on the surface. The modelling results indicated that the primary parameters influencing the predicted time for complete system saturation and HWC formation are the catchment-to-garden area ratio and the filtration coefficient. The WRC of soil materials and the depth of the system layers significantly impact the time required for full saturation and water filling but have minimal effect on the surface HWC. It was demonstrated that a rain garden with a depth of 1.2 m, a catchment-to-garden area ratio of 15, and a filtration coefficient of 100-200 cm/h functions effectively under critical rainfall intensities. The developed model and the resulting data, providing precise calculations and design recommendations, can be utilised by engineers and planners to optimise rain garden designs, thereby enhancing stormwater management efficiency

✓ **Keywords:** stormwater management; filtration coefficient; water retention capacity; catchment to garden area ratio; height of the water column

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Introduction

Rapid urbanisation and increasing development significantly reduce the permeability of natural land surfaces. This leads to intensified stormwater runoff, a heightened risk of urban flooding, reduced infiltration rates, and higher concentrations of heavy metals and other pollutants in stormwater. Additionally, climate change disrupts precipitation patterns across various regions, resulting in unpredictable rainfall volume and intensity increases. In many countries, including Ukraine, the situation is further exacerbated by insufficient drainage systems for stormwater collection and the limited efficiency of existing sewerage infrastructure, contributing to prolonged waterlogging. These urban challenges cause substantial economic losses, such as damage to agricultural production, urban and rural property, and hydraulic infrastructure, while also exerting significant negative impacts on the environment.

According to C. Jiang *et al.* (2019), stormwater management technologies can be classified into two primary categories: systems based on water infiltration and systems designed for stormwater retention. Infiltration-based systems facilitate the restoration of stormwater flows by replenishing groundwater and subsurface water reserves. Examples include catchment basins, infiltration trenches, bioretention systems (rain gardens), sand filters, and porous pavement. Retention systems, such as wetlands, ponds, green roofs, and rainwater harvesting systems (storage tanks and basins), are intended to slow the flow of water. The operational efficiency of rain garden structures largely depends on three key factors influencing their capacity to manage stormwater. The primary factor affecting infiltration capacity and the volume of retained stormwater is the hydraulic conductivity or filtration coefficient of soil materials, making soil type a critical determinant in retaining stormwater runoff and removing pollutants, as noted by G. Li *et al.* (2021). Furthermore, C. Jiang *et al.* (2019) highlighted that the water retention capacity (WRC) of soil materials is another important characteristic influencing the hydraulic processes within rain gardens. Concerning the structural features of rain gardens, the retention and treatment of stormwater can be enhanced by optimising key design dimensions, such as the depth of the surface depression zone and the thickness of soil layers, as indicated by E. Burszta-Adamiak *et al.* (2023). Variations in environmental conditions across different geographic regions result in differing hydrological process outcomes for identical rain garden designs. Consequently, various models have been developed to provide more precise tools for evaluating the efficiency of rain garden structures, aiding urban planners in stormwater management strategy development.

One widely used model is the Storm Water Management Model (SWMM), which features a flexible infiltration module suitable for landscape-scale applications. This module incorporates surface infiltration using the Green-Ampt method, porous media flow governed by Darcy's law, and groundwater infiltration, as discussed by W.A. Lisenbee *et al.* (2022). The DRAINMOD model,

highlighted by J. Kim *et al.* (2023), is commonly employed for rain garden simulations, with infiltration described by the Green-Ampt equation. It requires users to input the soil-water characteristic curve and the parameter for saturated hydraulic conductivity. According to W. Lisenbee *et al.* (2020), DRAINMOD has recently been adapted for urban stormwater management applications. In Australia, the Model for Urban Stormwater Improvement Conceptualisation (MUSIC) serves as the industry standard for modelling rain gardens and other stormwater control measures, as noted by A. Hoban & C. Gambirazio (2021). In MUSIC, infiltration in rain gardens is described using Darcy's equation for flow through porous media, accounting for soil texture and moisture content. Richards' equation is employed to model flow within rain gardens, enabling predictions of peak runoff rates and reductions in stormwater volume. One such numerical model, as referenced by G. Li *et al.* (2021), is known as RECHARGE. This model facilitates the analysis of rain garden infiltration behaviour to support their design and performance evaluation. Since its development, the RECHARGE model has only been validated under isolated phenomena in controlled experimental conditions. However, it has not yet been tested in real-world scenarios or over extended periods encompassing multiple rainfall events. The study by W. Nichols *et al.* (2021) discussed the HYDRUS software packages, which are finiteelement variably saturated models that numerically solve Richards' equation to describe unsaturated water flow. While this approach provides a physically robust and high-resolution simulation of infiltration processes, the model is not specifically tailored for rain gardens. In the study of M. Kravchenko *et al.* (2024a), a universal mathematical model was developed using Darcy's equation. This model offers a detailed description of infiltration processes at specific moments in time, incorporating the height of the water column (HWC) on the surface of the structure.

Despite the extensive body of research on rain gardens, the principles for designing effective systems and accurately predicting their stormwater retention performance during operation remain pressing issues requiring further investigation and refinement. This study aimed to examine the influence of engineering parameters – such as the depth of the structure, the catchment-to-garden area ratio, the filtration coefficient, and the WRC – on the efficiency of hydrological processes, using a universal hydrological model. Based on the results obtained, an optimal system configuration was proposed to enhance rain garden performance.

Materials and Methods

To achieve the research objective, a previously developed hydrological mathematical model (Kravchenko *et al.*, 2024a) was utilised, and implemented in Scilab software. The parameters incorporated into the hydrological infiltration model, accounting for HWC and the filtration coefficient, are described in Table 1.

Table 1. Parameters included in the mathematical infiltration model considering HWC and the filtration coefficient

Parameter	Description	Unit of measurement
A_{bassin}	Catchment basin area	m ²
A_{sponge}	Area of the rain garden structure	m ²
H_{sponge}	The total depth of the rain garden structure	m
A_{h_0}	Rain garden area as a function of height h_0 from the upper level	m ²
v_r	Inflow rate of stormwater into the system	m/c
h_0	HWC	m
w	Initial moisture content of soil mixtures	m ³ /m ³
w_{sat}	WRC of soil mixtures in a saturated state	m ³ /m ³
k_f	Filtration coefficient of soil mixtures	cm/h
δ_j	The thickness of the j -th layer of the rain garden	m
τ	Saturation and filling time of the rain garden	c
y_i	Depth of penetration and saturation of the rain garden structure with stormwater at the current time step τ	m
i, j, n, m	Soil layers of the rain garden, starting with the first layer ($j = 1$) and ending with layer ($m - 1$) where saturation occurs at a specific moment in time	No.

Source: developed by the authors

Assuming that rainfall occurs at a relatively constant intensity over a given period, the total volume of water that a rain garden can retain can be considered as the sum of the water volumes that can be stored on the surface within the depression zone and infiltrated during the rainfall event. This relationship can be used to determine the required surface area of the rain garden according to the equation proposed by the authors:

$$A_{sponge} = \frac{A_{bassin} \times c \times P}{h_0 \times k_{fsponge} \times \tau_r}, \tag{1}$$

where c is the average runoff coefficient of the catchment area; P is the maximum rainfall depth calculated for the

rain garden, m; $k_{fsponge}$ is the filtration coefficient (saturated hydraulic conductivity) of the rain garden, cm/h; and τ_r denotes the duration of stormwater inflow into the structure, hours. For small catchment areas, the time difference between rainfall and runoff is usually minimal, allowing τ_r to be approximated as the rainfall duration. The parameter h_0 is particularly significant for predicting the rain garden's capacity to manage runoff from highintensity rainfall events and in scenarios where infiltration capacity diminishes due to factors such as system clogging or a decrease in ambient air temperature. The value of HWC was calculated using the following equation:

$$h_0 = \max \left(\left(v_r \times \frac{A_{bassin}}{A_{sponge}} - \frac{d(h_0 \times A_{h_0})}{A_{sponge} d\tau} \right) \times \left(\sum_{j=1}^{n-1} \frac{\delta_j}{k_{f,j}} + \frac{y_i - \sum_{j=1}^n \delta_j}{k_{f,n}} \right) - y_i, 0 \right), \tag{2}$$

where d is the differential or variable of $h_0 \times A_{h_0}$; $d\tau$ is the differential or variable of the time parameter τ . The process of water percolation and saturation through the layers of

the structure, from the depression zone in the uppermost layer of the rain garden to the depth y_p , is described by the following equation:

$$\begin{aligned} & \frac{A_{bassin}}{A_{sponge}} \times \left(\int_0^\tau v_r \times d\tau \right) - \int_0^{h_0 \times \frac{A_{h_0}}{A_{sponge}}} d \left(h_0 \times \frac{A_{h_0}}{A_{sponge}} \right) = \\ & = \int_0^{y_i} w_{sat} \times dy_i = \sum_{j=1}^{m-1} (w_{sat,j} \times \delta_j) + w_{sat,m} \times (y_i - \sum_{j=1}^{m-1} \delta_j). \end{aligned} \tag{3}$$

The position y_i at time τ , accounting for the height h_0 on the surface of the structure, was determined using the equation:

$$\begin{aligned} y_i(\tau) = & \frac{A_{bassin}}{A_{sponge}} \times \left(\int_0^\tau v_r \times d\tau \right) - \\ & - h_0(\tau) \times \frac{A_{h_0}(\tau)}{A_{sponge}} - \frac{\sum_{j=1}^{m-1} (w_{sat,j} \times \delta_j)}{w_{sat,m}} + \sum_{i=1}^{m-1} \delta_j. \end{aligned} \tag{4}$$

By integrating Darcy's equation from the boundary y_a in layer n_a to the boundary y_b in layer n_b , with consideration

of HWC and the filtration coefficient, the rate of stormwater infiltration into the system was determined using the following equation:

$$v_r \times \frac{A_{bassin}}{A_{sponge}} - \frac{d(h_0 \times A_{h_0})}{A_{sponge} d\tau} = k_f(y) \times \frac{dh}{dy}. \tag{5}$$

Under the condition of full water saturation of the structural layers, the rate of water inflow into the rain garden or drainage system was determined according to the equation:

$$v_{out} = v_r \times \frac{A_{bassin}}{A_{sponge}} - \frac{d(h_0 \times A_{h_0})}{A_{sponge} d\tau}. \tag{6}$$

The methodology is detailed further in M. Kravchenko *et al.* (2024b). Infiltration represents a portion of the total stormwater inflow into the rain garden structure, moving vertically into the soil rather than being diverted to an overflow pipe. The infiltration rate decreases exponentially with increasing rainfall intensity (P), with the most significant reductions observed during low and moderate-intensity events ($P < 10$ mm). Therefore, the developed model was applied to optimise the parameters of the rain garden for maximum water retention within the structure and enhanced infiltration. The hydrological model simulates a single event with a rainfall intensity of 36 mm/h to evaluate the rain garden's performance under extreme conditions. This event was selected based on meteorological observations from the Borys Sreznevsky Central Geophysical Observatory, which recorded a historic rainfall event over the past 16 years (2007-2023) in Kyiv, Ukraine, on 22 July 2023.

The rainfall amounted to 36 mm/h, equivalent to 36 dm³/m² in one hour.

Modelling the infiltration processes occurring within a rain garden requires the input of actual values for the WRC and filtration coefficient of the soil layers in the system. Experimental cylindrical columns replicating the basic structure of a rain garden were established in the Environmental Parameter Control Laboratory at Kyiv National University of Construction and Architecture (Ukraine). The model structure consisted of three main layers: an upper layer of natural soil, an intermediate sand layer, and a lower gravel-based drainage layer (Fig. 1a). The upper natural soil layer, characterised as loamy sand, is designed for planting vegetation and collecting rainfall through a surface depression zone. This soil material, used for experimental investigations, was sampled from an area in Kyiv at a depth of up to 200 mm. The intermediate layer, responsible for infiltration, comprised river sand. The lower layer functions as drainage to divert water from the system, with gravel of particle sizes ranging from 3 to 7 mm selected as the soil material.

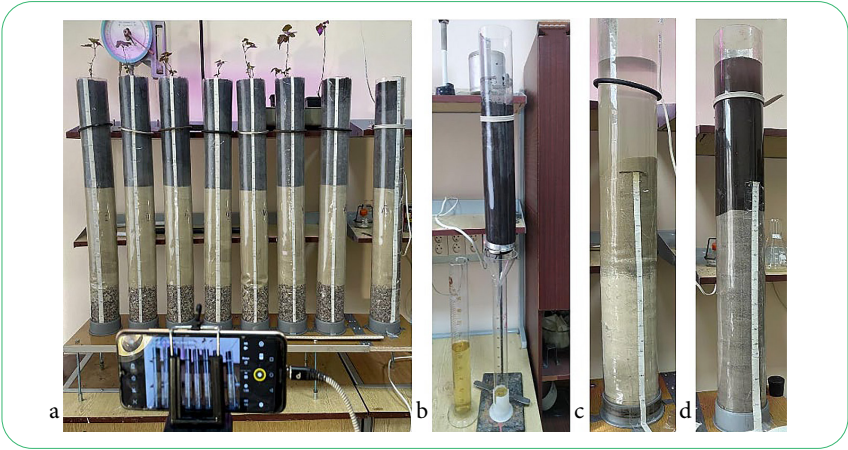


Figure 1. Experimental rain garden constructions

Note: a – general view; b – determination of WRC of the soil layer; c – determination of the filtration coefficient of the sand infiltration layer; d – determination of the filtration coefficient of the natural soil layer

Source: developed by the authors

The primary aim of the experimental setup was to investigate the filtration capabilities of rain gardens, specifically their ability to remove petroleum pollutants from simulated rainwater. Diesel fuel and used motor oil, the most common pollutants in this category, were selected for modelling petroleum hydrocarbons, as described in M. Kravchenko *et al.* (2024b). Concurrently with the experimental investigation, the WRC (Fig. 1b) and filtration coefficient (Fig. 1c; Fig. 1d) of the soil materials were determined under laboratory conditions. The filtration coefficient was assessed under vertical water flow from top to bottom, following saturation of the studied soil sample, following DSTU B V.2.1-23:2009 (2009). The experiments were conducted with constant pressure on the soil and variable water head. The WRC of the soil materials was determined using a method validated by J.T. Nelson *et al.* (2024), employing a funnel and filter paper. This parameter was

determined after complete saturation of the sample and free drainage, which lasted for two hours.

✔ Results and Discussion

Rain gardens: General characteristics

A bioretention system or rain garden structure is a landscaped depression designed to manage stormwater runoff effectively in urban areas. As outlined in M. Kravchenko *et al.* (2024c), the primary components of a rain garden system (Fig. 2) include a depression zone for collecting rainwater, vegetation on the surface, a substrate (growing medium), an infiltration layer, a drainage layer, and an underlying drainage system (if required). Stormwater runoff is captured and temporarily stored within the rain garden structure and on its surface in the depression zone. Subsequently, the water infiltrates vertically into the soil medium or discharges into the existing stormwater drainage system.

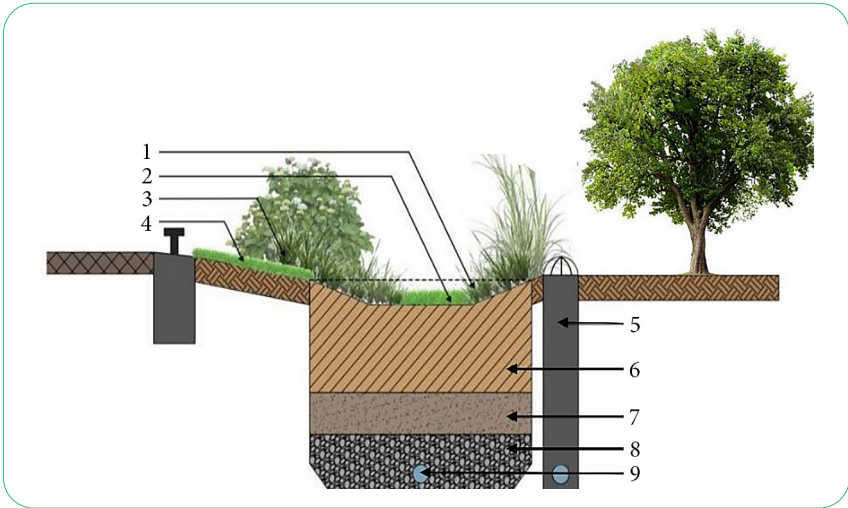


Figure 2. Key elements of a rain garden construction, cross-section

Note: 1 – depression zone for collecting and forming a column of rainwater; 2 – a layer of soil cover materials (mulch); 3 – plant layer; 4 – grass cover; 5 – overflow system; 6 – upper soil layer (for planting plants); 7 – intermediate infiltration layer; 8 – gravel layer; 9 – drainage system

Source: developed by the authors

Special attention should be given to the depression zone in the upper layer of the rain garden, which is designed to collect stormwater runoff from the catchment area and rainwater during precipitation. In this zone, a water column forms, the height of which depends on rainfall intensity and the hydraulic permeability of the system (Fig. 3).

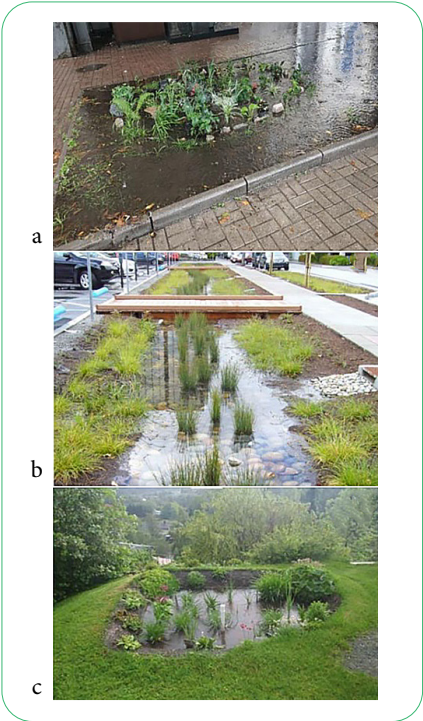


Figure 3. Examples of water column formation on the surface

Note: a – Ivan Mazepa Street, Kyiv, Ukraine; b – San Mateo, California, USA; c – Melhus, Norway

Source: a – created by the authors; b, c – Rain gardens (2023)

The value of HWC is a critical parameter for predicting the infiltration performance of the structure and the potential for overflow. If the rain garden medium becomes fully saturated and the depth of the depression zone reaches its maximum height, overflow occurs. The depth of the depression zone is typically designed within a range of 15 to 30 cm. The presence of a water column in the depression zone is essential for supporting plant and microbial communities during prolonged dry periods and for creating an anaerobic environment that facilitates pollutant removal processes (Goh *et al.*, 2019). However, during frequent rain events, the depression zone may remain continuously filled with water, increasing the risk of mosquito proliferation, overwatering of plants, and soil compaction.

At the onset of a rainfall event, surface runoff is generated, with its volume directly proportional to the intensity of precipitation. Stormwater from the catchment area flows into the depression zone in the upper layer of the rain garden, where it infiltrates vertically through the multi-layered structure. If the inflow rate exceeds the infiltration capacity of the rain garden layers, water accumulates in the depression zone, forming a column with a height of h_0 . During high-intensity rainfall, the depression zone may become fully saturated, resulting in overflow. The infiltration process within the rain garden continues as long as water inflow persists or until the depression zone is completely emptied ($h_0 = 0$).

Rain garden models can be categorised into two main types. The first category comprises nonphysically-based models, which are predominantly statistical and tailored to specific experimental sites. These models require only a limited number of parameters for implementation but are often case-specific and challenging to adapt to varying climatic conditions. Additionally, they offer limited predictive capabilities. The second category includes physically-based models, which are numerically more complex. As noted by

N. Alamdari & D.J. Sample (2019), such models typically require significant calibration efforts or access to detailed soil parameters that are difficult to estimate, such as the soil water retention curve. The simulation of infiltration processes in rain gardens is conducted by modelling rainfall events to predict the system’s response to changes in precipitation characteristics. Rainfall characteristics are a critical factor to consider during the design phase of rain gardens. Regardless of the arrangement of structural layers within the system, the intensity of prolonged rainfall events may exceed the infiltration rate of the soil layers, leading to surface water accumulation and system overflow.

The experimentally determined water retention capacities (w_{sat}) were as follows: the top layer of natural soil $w_{sat1} = 0.33 \text{ m}^3/\text{m}^3$; the middle sandy layer $w_{sat2} = 0.31 \text{ m}^3/\text{m}^3$; and the bottom gravel layer $w_{sat3} = 0.1 \text{ m}^3/\text{m}^3$. Similar water retention values were also reported by J. Wang *et al.* (2019). Using the RECHARGE model, the authors evaluated rain garden performance as a function of three parameters: retention depth, the ratio of catchment area to rain garden area, and the saturated hydraulic conductivity of the soil medium. The simulated rain garden design was analogous to the experimental setup presented in this study, consisting of the following layers: the root zone (upper soil layer), transition zone (intermediate infiltration layer), and subsoil layer (gravel). The water retention capacities of these layers were determined by the authors as 0.3/0.35/0.2 m^3/m^3 .

The activity coefficients of the soil mixtures were determined as follows: upper soil layer $k_{\alpha} = 7.0 \text{ cm/h}$; intermediate/infiltration sandy layer $k_{\beta} = 45.0 \text{ cm/h}$; bottom gravel layer $k_{\gamma} = 200.0 \text{ cm/h}$. H. Takaijudin *et al.* (2019) experimentally identified the filtration coefficient of loamy sand soil (50% river sand and 50% natural soil) as 107.2 mm/h, equivalent to 10.72 cm/h. Furthermore, the filtration coefficient of a predominantly sandy soil mixture (90% river sand and 10% natural soil) was 569.67 mm/h (56.967 cm/h), which aligns closely with the values obtained in this study. R. Liu & E. Fassman-Beck (2018) measured the unsaturated hydraulic properties of artificial media with varying compositions, determining an unsaturated hydraulic conductivity (k_p) for marine sand at 0.013 cm/s, equivalent to 48.6 cm/h, which also corresponds to the results presented.

Design parameters of rain gardens

According to G. Li *et al.* (2021), the optimal depth of a rain garden system is influenced by soil conditions, the rooting depth of the planted vegetation, and the intended function. B. Zhang *et al.* (2020) investigated the impact of soil layer thickness on the performance of rain gardens. Their study

found that a taller structure (1.2 m) retained stormwater effectively at a rate of 80%, whereas shorter configurations (0.5-0.6 m) achieved only 44% efficiency. The upper soil layer consists of a mixture of organic soil, sand, loamy sand, or loamy, providing suitable conditions for plant growth. The thickness of this layer in a rain garden should depend on the flood tolerance and water permeability of the plants and typically ranges from 10 to 40 cm (Sittisom *et al.*, 2022). This layer should also have sufficient organic matter content to support vegetation growth and a high infiltration capacity. The intermediate layer enhances the permeability of the upper soil and is crucial for the infiltration process. It usually comprises fine gravel or coarse sand. This layer should be well-drained and robust enough to support the weight of the upper layers. The porosity of the intermediate layer should range between 20% and 40%, and its depth should be between 20 and 60 cm (Sittisom *et al.*, 2022). The bottom drainage layer consists of medium to coarse gravel and is designed to retain and temporarily store water before discharging it into the drainage system. The thickness of the gravel layer is calculated based on the density of the infiltration layer but should be no less than 30 cm.

Rain garden designs are generally suitable for small catchment areas. According to design guidelines, the catchment area should not exceed 0.8 hectares (Rain garden and bioretention..., 2017). Larger catchment areas may result in intense and voluminous runoff, increasing the risk of erosion and forming a substantial water column on the surface. To manage large catchment basins, these can be divided into smaller sub-catchments with multiple rain gardens constructed to accommodate runoff effectively. Guidelines recommend that the rain garden’s area should constitute 4-10% of the total catchment area (Bioretention..., n.d.). This ratio is considered somewhat conservative; in some cases, specific design requirements, such as rainfall volume and event duration, should also be taken into account. Using laboratory-determined values for WRC (0.33/0.31/0.1 m^3/m^3) and filtration coefficients (7/45/200 cm/h) of the soil layers, the hydrological behaviour of the rain garden was modelled. The model considered HWC as a function of varying area ratios (Table 2). The layer thicknesses were set at fixed values of 0.25/0.4/0.3 m (total depth of 0.95 m) based on the authors’ assumptions. As recommended by D. Rinchumphu *et al.* (2023), the effective area of the rain garden is considered to be 4-10% of the catchment area. The simulation examined the hydrological behaviour of the rain garden by varying the A_{bassin}/A_{sponge} ratio from 5 to 25. The analysis accounted for a rainfall intensity of 36 mm/h, the time for complete saturation and filling of the structure, and the resulting HWC on the surface.

Table 2. Impact of the area ratio A_{bassin}/A_{sponge} on the stormwater retention efficiency of the rain garden system considering HWC

Parameters	Rain garden design					
	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
A_{bassin}, m^2	100	100	100	100	100	100

Table 2, Continued

Parameters	Rain garden design					
	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
A_{sponge} , m ²	4	5	6.6	10	13	20
A_{bassin}/A_{sponge}	25	20	15	10	7.5	5
h_0 , m	0.5995	0.4656	0.3329	0.2016	0.1367	0.0725
τ , s	4,231	4,665.5	5,289	6,385	-	6,264.5

Note: - - the time is not specified because, during the 7,200 seconds of the simulation, full saturation and filling of the structure were not observed

Source: developed by the authors

The modelling results, presented as curves in Figure 4, indicate that the area ratio significantly influences the infiltration process within the rain garden structure. The curves in the upper section of the graph correspond to changes in HWC in the upper layer of the rain garden, while those in the lower section represent the saturation depth within the system. Each curve representing the depth of saturation in the rain garden is divided into four segments: three correspond to full saturation of the respective layer of the structure, and the fourth segment, a horizontal line parallel to the abscissa axis, corresponds to the state of complete filling of the system with stormwater.

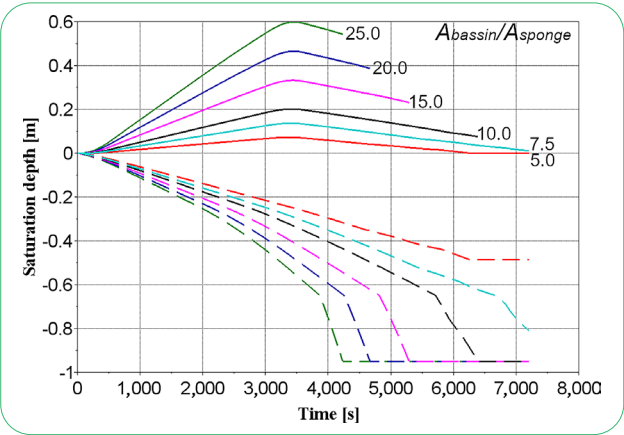


Figure 4. Dependence of the depth of saturation of the rain garden design and changes in HWC over time on the value of the area ratio A_{bassin}/A_{sponge}

Note: green line – rain garden design No. 1; blue – No. 2; pink – No. 3; black – No. 4; light blue – No. 5; red – No. 6

Source: developed by the authors

The results demonstrate that at an area ratio of 25, the rain garden structure reaches full saturation at a depth of 0.95 m within 1 hour and 10 minutes (4,231 seconds). At this point, the HWC value is 0.5995 m, exceeding the recommended range of 0.15–0.3 m (Ellis & Bettin, 2022). For instance, if a rain garden with an area of 4 m² is constructed to manage runoff from a 100 m² catchment area under a rainfall intensity of 36 mm/h, the system would not operate efficiently. Increasing the rain garden area (and consequently reducing the area ratio) enhances hydrological

performance, as evidenced by a longer filling time and a lower water column height. However, based on an analysis of logarithmic relationships, J. Lee *et al.* (2022) observed that pollutant removal efficiency tended to improve with an increase in the area ratio.

The modelling results indicate that the optimal A_{bassin}/A_{sponge} ratio is 15, corresponding to a rain garden area of 6.6 m², which falls within the recommended range of 4–10% of the catchment area. At this ratio, the system filling time is 1 hour and 28 minutes (5,289 seconds), with a surface water column height of 0.3329 m. This finding aligns with the study by W. Nichols *et al.* (2021), which utilised the HYDRUS-1D model to assess the efficiency of rain gardens for improved stormwater management. The study found that maximum rain garden efficiency could be achieved at an A_{bassin}/A_{sponge} ratio of 15. Similarly, research by L. Zhang *et al.* (2020) demonstrated effective rain garden performance at an area ratio of 13.78, using a mean rainfall intensity of 28.18 mm/h, comparable to the intensity used in the present study’s simulations. The findings of L. Bortolini & G. Zanin (2019) further support these results, showing that in the flat environment of Veneto, rain gardens sized at 10–15% of the roof drainage area can provide sustainable stormwater management alongside high aesthetic functionality.

The effectiveness of rain gardens with areas exceeding the recommended values of 4–10% of the catchment area was evaluated for areas of 13 and 20 m² (area ratios of 7.5 and 5, respectively) were evaluated. As shown in Figure 4, at $A_{bassin}/A_{sponge} = 7.5$, no complete filling of the structure occurs at a depth of 0.8 m within a simulation time of $\tau = 2$ hours (7,200 seconds), and a surface water column forms with a height of 0.1367 m. The smallest HWC value ($h_0 = 0.0725$ m) is observed at an area ratio of 20; however, at this ratio, the system becomes fully saturated after 1 hour and 44 minutes (6,264.5 seconds), reaching a depth of 0.487 m. A comparative analysis of marginal retention increases across four area ratio values by J. Wang *et al.* (2019) demonstrated that as the catchment area increases, the percentage of stormwater retained by the rain garden decreases. This is attributed to the infiltration volume approaching the total inflow, imposing a limit on further retention. Higher infiltration rates can be achieved not only by increasing the rain garden area but also by modifying the depth of its layers. Moreover, J. Wang *et al.* (2019) identified that the filling

volume of the surface depression in a rain garden depends more on the structural characteristics of the garden than on the infiltration flow rate. By increasing the construction depth by 0.3 m, changes in stormwater retention efficiency

considering HWC were obtained (Table 3). Figure 5 illustrates the relationship between the saturation depth of rain garden layers and HWC variation over time as a function of total construction depth H_{sponge} , m.

Table 3. Effect of the total depth of H_{sponge} on the stormwater retention efficiency of the rain garden system considering HWC

Parameters	Rain garden design			
	No. 1	No. 2	No. 3	No. 4
H_{sponge} , m	0.6	0.9	1.2	1.4
δ_1 , m	0.1	0.2	0.3	0.4
δ_2 , m	0.2	0.4	0.5	0.6
δ_3 , m	0.3	0.3	0.4	0.4
A_{bassin}/A_{sponge}	15	15	15	15
h_0 , m	0	0.3213	0.3388	0.3415
τ , s	2,500	4,588	6,747.5	-

Note: - – the time is not specified because, during the 7,200 seconds of the simulation, full saturation and filling of the structure were not observed

Source: developed by the authors

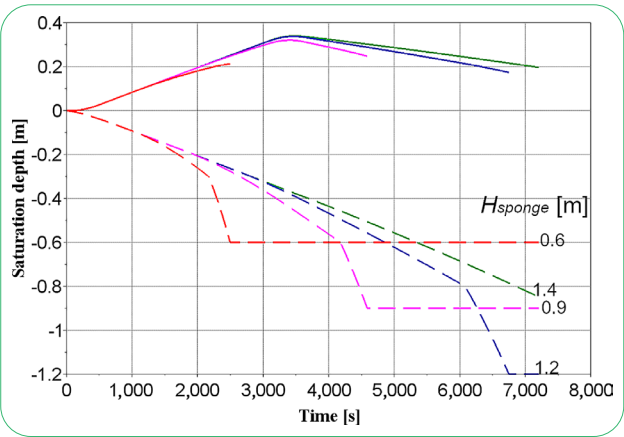


Figure 5. Dependence of the saturation depth and HWC variation over time on the total depth of the rain garden design, H_{sponge}

Note: red line – rain garden structure No. 1; pink – No. 2; blue – No. 3; green – No. 4

Source: developed by the authors

At a minimum depth of $H_{sponge} = 0.6$ m, the rain garden fills with stormwater within 42 minutes (2,500 seconds), with no surface water column ($h_0 = 0$). Increasing the depth of the structure by increments of 0.3 m extends the time for complete filling by an average of 38 minutes (2,258 seconds). However, the height of the surface water column changes by an average of just 0.01 m, indicating a minimal effect of H_{sponge} on this parameter. At the maximum depth of $H_{sponge} = 1.4$ m, the system does not reach full saturation within 2 hours (7,200 seconds), with a surface water column height (h_0) of 0.334 m, aligning with recommended values. A study by E. Burszta-Adamiak *et al.* (2023) assessed the efficiency of a rain garden in urban settings for capturing runoff from a 73.0 m² rooftop. The

total area of the rain garden was 7.6 m². Although the system had a maximum depth of 0.3 m, the results showed that the rain garden exhibited favourable hydrological performance under rainfall depths of up to 5.3 mm and durations of up to 10 hours and 33 minutes. G.M. Bethke *et al.* (2022) utilised the Environmental Protection Agency’s SWMM (EPA-SWMM) to evaluate the hydrological performance of rain gardens across varying environmental conditions. Their findings identified the thickness of soil materials and soil porosity as critical factors influencing the filling and overflow processes in rain garden structures.

Water retention capacity of a rain garden

The relationship between water content θ and matric potential ψ in soil under equilibrium conditions is referred to as the water retention characteristic or WRC. It represents the maximum volume of water that soil can retain when saturated. When the soil transitions from a saturated to an unsaturated (drier) state, the matric potential decreases from zero to a negative value. This parameter is significant because: it allows for the assessment of water availability in the soil environment for plants and enables irrigation management; it serves as a key hydraulic property for modelling unsaturated water flow in the soil layers of a rain garden; WRC reflects the effective pore size distribution within the medium. An increase in WRC is associated with higher infiltration rates and reduced runoff, especially during intense rainfall events (Williams *et al.*, 2018). The WRC of soils is primarily influenced by pore quantity, pore size distribution, and the specific surface area of the soil. As bulk density decreases, pore distribution changes, with a higher proportion of small pores emerging, particularly in coarse-textured soils (Abdallah *et al.*, 2021). For example, sandy soils have a significantly smaller surface area than clay soils and therefore retain much less water under higher stresses.

Additionally, the WRC of soil can also be improved by increasing the organic matter content (Libohova *et al.*, 2018). The addition of organic materials enhances the specific surface area of soil, thereby increasing its WRC. J. Hallam & M.E. Hodson (2020) investigated the impact of the anecic earthworm *Lumbricus terrestris* and the endogeic earthworm *Allolobophora chlorotica* on aggregate formation and WRC across different soil types (loam, silty loam, and loamy sand), noting a significant increase in WRC. F.G.A. Verheijen *et al.* (2019) studied the effect of biochar on bulk soil density and WRC under laboratory conditions using two agricultural soils from Portugal: sandy and loamy sand. The findings indicated that the addition of biochar

effectively improved the soil's WRC. Similarly, in a study by M. Nuruddin & A.A.B. Moghal (2024), soil amended with biochar exhibited substantial improvements in WRC, ranging from 16% to 274.1%, depending on the biochar content (0-100%). The effects of soil layer WRC on the ability of a rain garden to retain stormwater, including considerations of HWC, are presented in Table 4. The modelling results, illustrated as curves in Figure 6, reveal that variations in WRC of the upper natural soil layer (w_{sat1}), the middle infiltration layer (w_{sat2}), and the lower gravel layer (w_{sat3}) influence the degree of water saturation and the time required for full saturation of the rain garden system. However, the HWC value at the surface remains nearly unchanged.

Table 4. Impact of soil layer WRC (w_{sat}) on stormwater retention efficiency in a rain garden system considering HWC

Parameters	Rain garden design			
	No. 1	No. 2	No. 3	No. 4
$w_{sat1}, \text{ m}^3/\text{m}^3$	0.42	0.36	0.34	0.30
$w_{sat2}, \text{ m}^3/\text{m}^3$	0.36	0.34	0.32	0.28
$w_{sat3}, \text{ m}^3/\text{m}^3$	0.15	0.15	0.1	0.1
A_{basin}/A_{sponge}	15	15	15	15
$h_0, \text{ m}$	0.3290	0.3320	0.3326	0.3334
$\tau, \text{ s}$	6,386	5,924	5,418	4,907

Source: developed by the authors

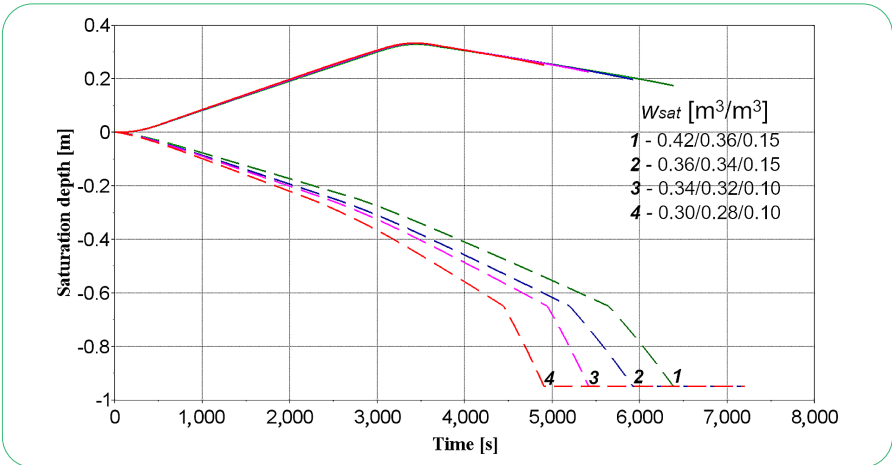


Figure 6. Relationship between rain garden saturation depth and HWC changes over time as a function of WRC (w_{sat})

Note: green line – rain garden design No. 1; blue – No. 2; pink – No. 3; red – No. 4

Source: developed by the authors

At the highest w_{sat} values of soil materials (0.42/0.36/0.15 m^3/m^3), the longest time to achieve full saturation of the rain garden system was recorded at 1 hour 46 minutes (6,386 s), with a surface water column height of 0.3290 m. Reducing WRC values resulted in a decrease in the time required for full saturation and complete filling of the system by an average of 8 minutes (493 s). Meanwhile, the value of h_0 on the surface of the structure remains practically unchanged at 0.33 m. As demonstrated by M. Kravchenko *et al.* (2024b), WRC influences the hydrological behaviour of rain gardens during modelling that does not account for the water column height. When the parameter h_0 is considered, WRC is not a primary characteristic for controlling

or modifying the functional efficiency of the system. These findings align with the conclusions of J. Wang *et al.* (2019), where WRC was evaluated through sensitivity testing. It was established that this parameter has a significantly smaller impact on hydrological processes in the rain garden compared to hydraulic conductivity.

Filtration coefficient of rain garden systems

The filtration coefficient of a rain garden is a measure of the hydraulic capacity of the system, which affects its ability to infiltrate surface water before the next rainfall event and manage prolonged low-intensity precipitation. For rain gardens in temperate climates, the recommended range of

k_f values is 100-300 mm/h (Adoption guidelines..., 2015). When selecting the filtration coefficient, previously recorded values from field studies of rain gardens can be used, or the parameter can be determined under laboratory conditions, as in the present study. If the soil is well drained and possesses a high infiltration capacity (e.g., greater than 10 cm/h), it can be used as a material for rain gardens. In cases where the soil has a low infiltration capacity, replacement with a specially designed soil mix may be required. For example, loamy sand and sand enhance infiltration, whereas a high clay content reduces soil permeability and pore size, diminishing the system's retention capacity (Putri *et al.*, 2023). Based on scientific findings, it is challenging to recommend a precise proportion of sand, clay, or silt in rain garden soil mixtures to achieve a sufficiently high filtration coefficient. However, H. Takaijudin *et al.* (2019) suggested a widely accepted soil mix composition of 30-60% sand, 20-40% compost, and 20-30% natural soil. Additionally, infiltration tests conducted in rain gardens by D. Técher & E. Berthier (2023) demonstrated that plant roots and the biological processes occurring around them increase soil porosity, thereby enhancing the infiltration rate of stormwater. Thus, it can be argued that the infiltration capacity of rain gardens will be sufficient if: sand predominates in the soil composition; plants with a developed root system

are planted in the upper soil layer; and there is no mechanical compaction of the soil medium. A low infiltration rate reduces the vertical movement of water through the soil and increases the HWC on the surface. As noted by J. Wang *et al.* (2019), lower infiltration capacity in rain gardens prolongs the presence of the surface water column, which may take up to 48 hours to recede. This condition can result in waterlogging of the vegetation and facilitate the proliferation of mosquitoes. Therefore, modelling the relationship between the stormwater retention efficiency of a rain garden and the variation in the filtration coefficient of its structure is critical during both the design and operational phases of these systems. In laboratory conditions, the filtration coefficients of soil layers in experimental rain gardens were determined as 7.0/45.0/200 cm/h. By altering the values for each layer, the overall filtration coefficient of the system ($k_{fsponge}$) can be adjusted. For the given water retention capacities (0.33/0.31/0.1 m³/m³), layer thicknesses of 0.25/0.4/0.3 m (total rain garden depth of 0.95 m), and an area ratio of $A_{bassin}/A_{sponge} = 15$, the dependency of stormwater retention efficiency on variations in $k_{fsponge}$ was derived during the modelling process (Table 5). As can be seen from the graphs of changes in the saturation depth of the rain garden layers and HWC over time depending on the filtration coefficient $k_{fsponge}$ (Fig. 7), this parameter has a significant impact on the hydrological behaviour of the system.

Table 5. Impact of filtration coefficient ($k_{fsponge}$) of soil layers on stormwater retention efficiency in rain gardens with consideration of HWC

Parameters	Rain garden design				
	No. 1	No. 2	No. 3	No. 4	No. 5
$k_{fsponge}$, cm/h	122.0	190.0	258.0	326.0	394.0
k_{f1} , cm/h	7.0	15.0	23.0	31.0	39.0
k_{f2} , cm/h	15.0	25.0	35.0	45.0	55.0
k_{f3} , cm/h	100.0	150.0	200.0	250.0	300.0
h_0 , m	0.3368	0.2476	0	0	0
τ , s	5,968.5	3,653	2,826.5	2,352	2,039

Source: developed by the authors

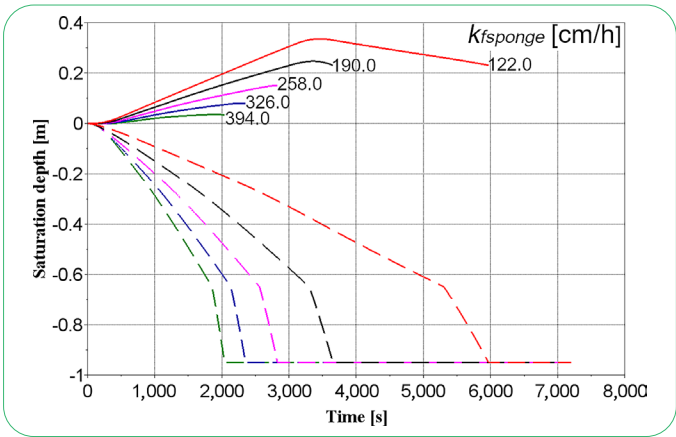


Figure 7. Dependence of the saturation depth of the rain garden structure layers and changes in HWC over time on the filtration coefficient $k_{fsponge}$

Note: red line – rain garden structure No. 1; black – No. 2; pink – No. 3; blue – No. 4; green – No. 5
Source: developed by the authors

At the minimum k_{sponge} of 122 cm/h, the rain garden structure reaches full saturation and fills with stormwater within 1 hour and 40 minutes (5,968.5 seconds). During this period, a water column 0.3368 m high forms on the surface of the rain garden. As the filtration coefficient increases, the system fills with water more quickly, and the surface HWC value decreases. For example, at k_{sponge} values of 326 and 394 cm/hour, the value of h_0 is 0 m, but the structure fills up quite quickly, in 39 minutes (2,352 s) and 34 minutes (2,039 s), respectively. In such cases, to ensure effective system operation and prevent overflow, it is necessary to include a drainage system that diverts excess stormwater into underground storage tanks or the sewer network. These findings align with results reported by J. Wang *et al.* (2019), which demonstrated that the highest productivity increase in rain gardens occurs when the filtration coefficient increases from 0.1 to 1 cm/h, with an area ratio of 17.5. Beyond k_f of 10 cm/h, the incremental productivity gain per unit increase in k_f diminishes, indicating a sharp decline in water retention time for k_f values below 10 cm/h. This highlights the particular sensitivity of rain garden performance to low k_f values (e.g., below 10 cm/h). Thus, at critical rainfall intensities (36 mm/h), a rain garden structure with a depth of 1.2 m (layer thicknesses of 0.3/0.5/0.4 m), an area ratio of 10 to 15, and a system filtration coefficient ranging from 100 to 200 cm/h can function effectively for up to 2 hours. This configuration significantly reduces the volume of stormwater and decreases surface runoff velocity. The main reasons for the differences with other studies are the different parameters of the rain garden structure setup, in particular, the properties of the soil materials.

✓ Conclusions

This study demonstrated that a mathematical infiltration model incorporating Darcy's equation effectively simulates rain garden performance based on variations in its key parameters. The analysis of results enables the selection of optimal structural characteristics and appropriate soil materials during the design phase, ensuring effective operation during the system's service life. For instance, the modelling results indicated that to ensure the efficient functioning of

a rain garden under critical rainfall intensity (36 mm/h), the system should meet the following parameters: a depth of 1.2 m (with layer thicknesses of 0.3/0.5/0.4 m), an area ratio of 10 to 15, and a filtration coefficient ranging from 100 to 200 cm/h.

The obtained results indicate that the ratio of the catchment area to the rain garden area and the filtration coefficient are the primary parameters determining the predicted time required for the system to fill completely and the formation of a water column on the surface. It was determined that the optimal $A_{\text{basin}}/A_{\text{sponge}}$ value is 15, corresponding to a system area of 6.6 m² for a catchment area of 100 m², which falls within the recommended range. Under these conditions, the system fills in 1 hour and 28 minutes (5,289 seconds) with a surface water column height of 0.3329 m. The model is significantly less sensitive to parameters describing the WRC of soil materials and the layer depths within the structure. It was found that changes to these parameters influence the time required for full saturation and system filling, while the surface HWC remains constant. A reduction in WRC decreases the total saturation and filling time by an average of 8 minutes (493 seconds). Increasing the system depth by 0.3 m extends the filling time by an average of 38 minutes (2,258 seconds).

For further refinement and enhancement of the proposed mathematical model, future research should focus on implementing rain gardens under real-world conditions. This approach would enable the calibration of the model based on empirical data, thereby improving prediction accuracy and the overall effectiveness of the system. Additionally, an important aspect of future investigations is the analysis of the influence of antecedent soil moisture from consecutive rainfall events. This would provide deeper insights into how systems respond to prolonged or intense precipitation and assess their resilience to frequent storms.

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None.

✓ Conflict of Interest

None.

✓ References

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Моделювання інфільтраційних процесів у дощових садах: вплив параметрів дизайну на гідрологічну ефективність

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✔ **Анотація.** Дощовий сад – це конструкція для управління дощовими водами на місці. Недосконалий дизайн дощового саду може погіршити його гідрологічні властивості під час експлуатації, що вимагає розробки та апробації відповідної математичної моделі для інженерного розрахунку й оцінки конструкції. Метою цього дослідження було моделювання процесу інфільтрації у дощовому саду на основі математичної моделі, яка враховує висоту стовпа води (BCV) на поверхні конструкції та коефіцієнт фільтрації ґрунтових матеріалів, імітуючи реакцію системи під час екстремальної дощової події (36 мм/год). Використовуючи розроблену модель, отримано розрахункові криві, що описують продуктивність дощового саду залежно від параметрів його дизайну: глибини конструкції, співвідношення площі водозбірного басейну до площі дощового саду, коефіцієнта фільтрації та водоутримувальної здатності (ВУЗ). Основні параметри ґрунтових матеріалів визначалися експериментальним шляхом у лабораторних умовах. Інфільтраційна продуктивність конструкції оцінювалася за зміною часу проникнення та насичення всіх шарів, а також заповненням водою дощового саду в результаті коригування його параметрів і змін BCB на поверхні. Результати моделювання показали, що основними параметрами, які визначають прогнозований час повного заповнення системи водою і формування BCB, є співвідношення площ та коефіцієнт фільтрації. ВУЗ ґрунтових матеріалів і глибина шарів конструкції суттєво впливають на час повного насичення і заповнення системи водою, але майже не впливають на BCB на поверхні. Показано, що конструкція глибиною 1,2 м, при співвідношенні площ 15 та з коефіцієнтом фільтрації 100-200 см/год ефективно функціонує при критичній інтенсивності дощових опадів. Розроблена модель і отримані результати, надаючи точні розрахунки та рекомендації щодо параметрів конструкції, можуть бути використані інженерами та проектувальниками для вдосконалення дизайну дощових садів, що сприятиме підвищенню ефективності управління зливовими водами

✔ **Ключові слова:** управління зливовими водами; коефіцієнт фільтрації; водоутримувальна здатність; співвідношення площ; висота водяного стовпа



Design thinking to avoid maladaptation in building climate change resilience of urban areas

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✔ **Abstract.** Adaptation of settlements to the climate change effects is an urgent task for researches and multiple stakeholders interested in efficient functioning of urban systems and safety of residents. The development of adaptation plans is complicated due to lack of certainty about the results of these actions. From the other hand, cases of maladaptation are already numerous, which is why this research was aimed at defining the principles of adaptation planning, which help to avoid the risks of maladaptation. The case of the joint project developed by Master students from Canada, Iceland and Latvia for the rehabilitation of the abandoned industrial facility in the centre of Kyiv, Ukraine, was used to analyse the drivers of maladaptation and suggest the principles of efficient implementation of climate adaptation into city development initiatives. The method of multi-criteria evaluation was used to compare possible post-rehabilitation projects and determine the role of selected factors if raising probability of maladaptation. The weight of factors, affecting the choice of the alternative, was set involving developers, specialists with the experience of designing adaptation plans, non-governmental organisations and researchers. The recommendations for the mitigation of the maladaptation risks in designing adaptation plans were developed and used to reconsider the results of the joint project and abandon the alternative prone to maladaptation. It was shown that climate issues should be considered as a separate category and target instead of including it into the broad category of environmental protection. Evaluation highlighted the importance of design thinking and system structure analysis for the multidisciplinary teams working on the urban development, involving adaptation actions. The results of the research are applicable for preparation of project groups, working on urban development and post-war-reconstruction, to guarantee efficient implementation of climate adaptation needs and prospects in corresponding plans

✔ **Keywords:** multi-criteria evaluation; urban development; expert assessment; environmental protection; adaptation to climate changes

✔ Introduction

Climate changes create complications for development at all levels of social organisation – from local communities to global regions. The information accumulated to date is vast, yet hard to cope with and needs certain expertise to

use it efficiently. At the same time, adaptation has already turned into an applied field of work, which is of high demand and obligate to fit into tight deadlines. Policymakers are working on frameworks, built on the research and

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analytical data, while local players are in need for clear plans and suggestions. The previous years of adaptation strategies implementation has yielded both positive and negative results, which might have different roots. At the same time, the analysis of 1,628 papers, conducted by L. Berrang-Ford *et al.* (2021), demonstrated that most of adaptation actions have fragmented character, which could be caused by lack of efficient design. D. Reckien *et al.* (2023) also noted the growing number of maladaptation cases, which raises the need to study them in detail and feed the insights into the development of new adaptation plans. Based on the study of the known cases of maladaptation M.F. Rahman *et al.* (2023) has strongly emphasised the value of understanding and building on local preconditions, when developing adaptation plans. This makes each adaptation plan unique and calls for thinking up some new approaches for each locality. Thus, in the development of such plans a component of design must be articulated and relevant actions and expertise embedded. The multi-criteria evaluation (MCE) has been proved to be efficient for the solution of various environmental tasks and W.-M. Wang & H.-H. Peng (2020) have demonstrated its efficiency for urban sustainable development planning in particular.

Resilience of ecosystems is a key for supporting healthy environment for humans and wildlife. Design and implementation of adaptation plans is therefore a part of building functional system of environmental safety. However, the experience of maladaptation is being accumulated, which calls for developing special set of skills and competences in this field. The training of specialists in the field of adaptation to climate changes is still not well developed and limited number of university programmes is offered in the field. K.H.D. Tang (2022) has offered a novel model of climate change education, based on three modules – knowledge, action competence and community involvement. This approach can help students as citizens, but there is also need in training professionals for these specific tasks. Most commonly, environmentalists of any specialisation are involved in the process of developing such plans, since they normally possess well-established background in climate change science and management of natural resources. However, it is now seen that such specialists often lack design skills and have little to no awareness about failure risks an adaptation falls under. Recognition of the need for adaptation and activity of nongovernmental groups is not enough for successful adaptation, it is more a question of efficient collaboration between parties, as it is shown by J.E. Taylor *et al.* (2023) in the study for Alaska. This means that the organisation of the adaptation planning is also a task to be performed by pre-trained professionals.

Ukrainian researches are also concerned with the need to develop education for climate adaptation. In particular, V. Fedoniuk & M. Fedoniuk (2022) offered to implement selective courses on climate adaptation to all potentially involved specialists. At the same time N. Klevtsova (2021) stated that there is a need to standardise the adaptation plans, but there is a lack of framework for that. Overall,

there is a need to develop framework for the development of successful climate adaptation plans with the focus on avoiding maladaptation as a potential outcome. Thus, the aim of the paper was to consider the role of design thinking in successful adaptation to climate changes and the importance of maladaptation consideration. The important insights of the research are principles of mitigating maladaptation risks in the process of designing adaptation solutions.

✓ Materials and Methods

The risk of maladaptation was considered on the example of a joint project developed by Master students from Canada, Iceland and Latvia, formerly living in Ukraine. All of them have successfully completed special course in climate adaptation and natural resources management. The project was developed with the assistance from the Environmental Unit of Egis Ukraine (International Developer Company) and was submitted to the International Competition of Adaptation projects – Team up for Climate – 2024. The project was developed for the central districts of Kyiv – Shevchenko and Solomianka, facing intensive growth of thermal pressure from the urban heat island (UHI), amplified by warming climate, which is common for many cities of temperate climate. The aim of the project was to shift the balance in the ecosystem toward more comfortable and safe living conditions by reducing the UHI. For this purpose, members of the working team chose the project site – mostly abandoned First Kyiv Machine-Building Plant. The list of post-rehabilitation alternative projects was elaborated and their design was drafted. Using the methods of multicriteria analysis the working group defined the best alternative for implementation. Later they took a short course of environmental design and were invited to revise their development accounting recommendations on the maladaptation risks reduction.

The interconnections in the system “residents-climate-living conditions” are extremely complicated and require cross-disciplinary efforts to solve. To facilitate this process, it was important to comprehend the structure and dynamics of such systems, which may be accomplished by conceptual modelling as an alternative to complex mathematical calculations. The given research generally followed the framework of multicriteria analysis, suggested by R. Stevens (2021). The general method in this case consisted of three basic phases. System description (sketch) is the process of defining and characterising a system in terms of its components (preferably different variables) and interactions. System structure analysis involved investigating internal linkages and creating a variable effect matrix, and MCE – forecasting the influence of factors on the circumstances for each scenario. The MCE focused on a single issue, allowing several scenarios to be evaluated. The study’s research topics were based on the environmental harm caused by the fuel storage fire. The MCE steps were designed to collect numerical data that describe the characteristics of the options under examination. For this the parameters with the effect on the system interactions defined were formulated. As a result, different scenarios or

alternatives under consideration reflected variations in these parameters. The next step was to determine parameter “weights” – their relative importance for the studied system.

In this research, pair-wise estimates of the relative importance of parameters by experts were used. The relative importance of factors was evaluated by the members of the project group and their supervisors (totally 8 persons) and the experts from the field of project development (2 experts, EGIS Ukraina), representatives of nongovernmental organisations with previous experience of climate adaptation projects designing (2 experts from National Ecological Centre of Ukraine) and researchers from Kyiv Aviation Institute (3 experts). All experts rated the weight of each factor relative to all others individually and mean values were defined mathematically. The factors included: necessary investments in development; expected economic potential of the project area after restoration; social benefits to the local community and city on the whole; environmental pollution reduction (in particular, air quality improvement) and UHI reduction potential; threats to adjoining objects, including residential areas, university campus, subway station and existing commercial facilities; traffic intensity, which is typically high in the centre of the city with its narrow streets not prepared for the car flow of modern times; aesthetic appeal of the developed area. The research was conducted according to American Sociological Association’s Code of Ethics (1997).

In methodological words, “utility” refers to the examination of standardised dependencies between the components influencing the situation, the evolution of an event inside a system, and the system’s state. This utility value ranges from zero to one. The particular form of the relationship between the utility and each parameter – whether linear, logarithmic, or otherwise – is derived using real data or reasoned assumptions and expert opinions about how each parameter’s range impacts the state of the system under study. The values for each “utility” parameter were determined based on the estimated linkages between this parameter’s range and its influence on the system “residents-climate-living conditions”. This process was facilitated by plotted utility functions, with each scenario shown separately. The total utility for each scenario was calculated using the following equation:

$$Total_{utility} = \sum w_i \times u_i$$

(1)

where w_i – is relative weight of each parameter; u_i – is utility value defined for each scenario. The resulting total utility is used to rank different scenarios from the perspective of their efficiency.

✓ **Results**

The city of Kyiv, Ukraine, is facing growing heat pressure due to climate changes and reduction of green spaces. Over the last 10 years, Kyiv has been repeatedly ranked among the top 30 capitals with the most polluted air. Compact structure of urban area does not allow for the development of green infrastructure to compensate the loss of natural areas, which provide thermal pressure relief and air pollution mitigation. Therefore, abandoned industrial sites offer a good opportunity for solving these problems, but needs careful considerations of the best alternative development for each specific case. The First Kyiv Machine-Building Plant (formerly Bilshovyk) was established in 1882 and after the revolution of 1917 was re-quipped to produce a variety of machines for heavy industry. In 1980s it shifted to the production of tires for big industrial vehicles. Part of the territory was gradually abandoned, since the specialisation of the enterprise was narrowed, but the remaining production is still functioning. In 2021 the enterprise was sold to the private company, but the given part belongs to the city (Morozov, 2021).

The site is located in the middle of the city and is facing objects of different functions, including residential, commercial and industrial buildings. It is also surrounded by one of the busiest highways of Kyiv and a subway station. Thus, the analysis of the development of such site is complicated, since land uses of different purposes are combined there. These functional components affect the necessary preparation and reclamation for the new land use and, of course, have impact on the possible type of use and cost of project development. At the first approximation the target of the development was formulated as a project most beneficial for the city. This has raised question what is considered to be beneficial, and the working group set up for: environment quality and climate resilience; sustainability; economic efficiency; infrastructure improvement; community well-being. Based on these expected benefits the group defined the factors most important for project alternatives comparison and their relative weighting (Table 1).

Table 1. Relative importance of the decision-making factors of in choosing the best alternative of the post-rehabilitation development

Factor	Weight
Necessary investments in development	19.66
Expected economic potential of the project area after restoration	17
Social benefits to the local community and city on the whole	14.33
Environmental pollution reduction (in particular, air quality improvement) and UHI reduction potential	20
Threats to adjoining objects, including residential areas, university campus, subway station and existing commercial facilities	5.17
Traffic intensity, which is typically high in the centre of the city with its narrow streets not prepared for the car flow of modern times	8.67
Aesthetic appeal of the developed area	1.33

Source: created by the authors

The list of alternative projects was developed accounting the diversity of interests and demands of different interested parties. This, of course, means that each stakeholder has “affinity” to certain type of development (Fig. 1).

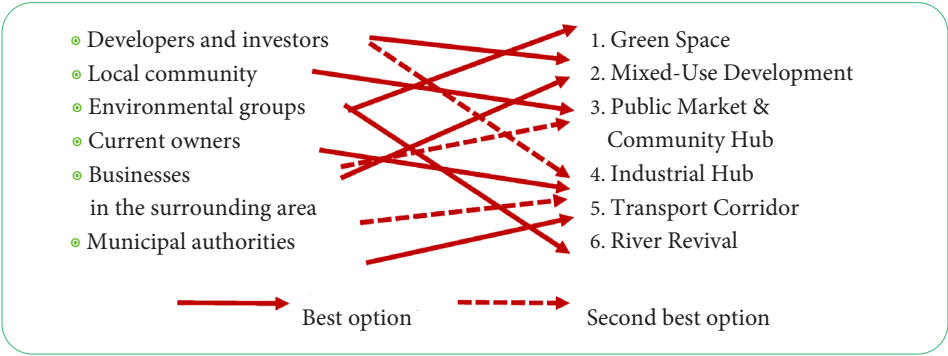


Figure 1. Stakeholders’ preferences in the choice of the post-rehabilitation development

Source: created by the authors

This would affect the weighting of the same factors done by each stakeholder; therefore, weighting of factors given here is intended to be a “mean” perspective. The resulted multi-criteria comparison of the defined alternatives showed that the best one in terms of benefits for the city was “Mixed-Use Development” (Fig. 2).

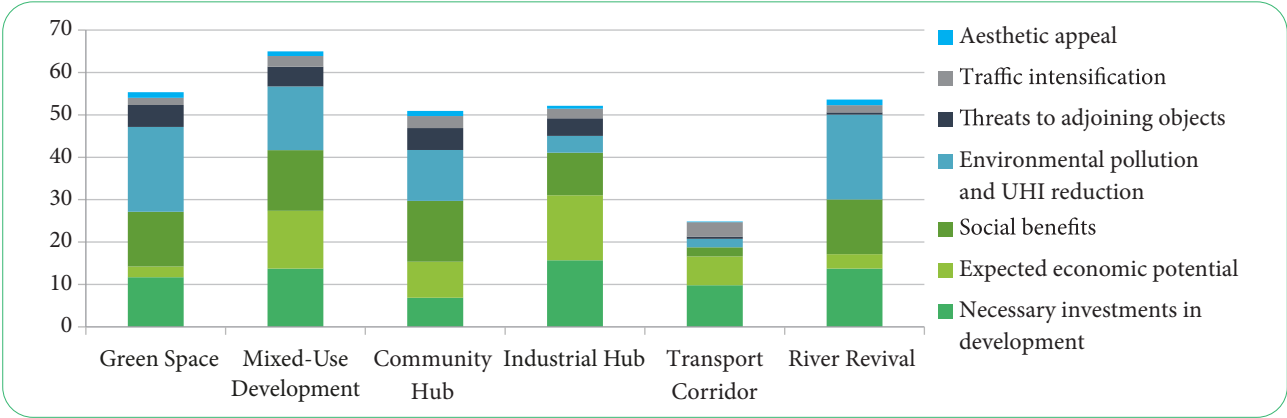


Figure 2. Comparison of the alternative development projects (without maladaptation prevention)

Source: created by the authors

This alternative was rated as an expensive, but the pay-back potential of this alternative was considered to be the most reliable and highest. Due to central location in the city and the demand for its residential and commercial areas would be high. Nevertheless, the central positioning of the site raised concerns about the quality of environment, in particular, air pollution levels are rather high, and this might reduce the attraction to the complex for families with children. Additionally, a well-planned and thorough remediation is necessary to remove possible health threats from the residual soil pollution at the territory. The second-best options were “Green Space” and “River Revival”, which offered the improvement of the state environment and the UHI reduction.

The lowest rating was set for “Transport Corridor”. This is the option, which is currently considered by the municipal authorities. However, despite its obvious importance for overloaded highway crossing by the site it would provide minimal benefits from other points, and it would

further contribute to traffic flow increase as a more suitable alternative pathway through the city. Therefore, it would eventually lead to the deterioration of environment quality and the UHI amplification. Going back to the initial purpose of this analysis it became obvious that negative externalities like those of the “Transport Corridor” were typical for the best option as well and in terms of climate changes response it was an obvious maladaptation.

Considering the given case of the First Kyiv Machine-Building Plant development and available analysis of maladaptation presented above, a complex of recommendations was suggested in order to reduce the risk of maladaptation. It is necessary to set the hierarchy of the project goals and formulate the primary target as climate change adaptation. This will automatically shift the focus of the design and assessment towards the needs of climate actions, instead of pursuing more general and thus inefficient goals. Putting adaptation on top will shape the list of alternatives and affect the weighting of factors so, that none of

stakeholders will be dominating over others. This, in turn, will facilitate setting compromises between stakeholders, since their primary aim will be out of the direct fields of interests. Separation of the factor of adaptation, or UHI reduction, as in the given case study, from others, even if they have strong connections as environmental pollution reduction, is decisive for efficient adaptation. It was found that low levels of air pollution did not guarantee that heat pressure would disappear or get minimised, instead it could mask the problem by giving false impression of it being managed in a bundle.

An object of study (facility, site, enterprise, area, etc.) should be viewed as a system. It is important to separate its structural elements or functional units and consider consequences of all suggested project alternatives on these structural elements. Without the development of special methodology for this step it is enough to contrast their expected changes to the points, listed as attributes of “beneficial project”, formulated as a target of the development. Since not all trends are obvious and easily predicted the “impact-effect” interactions between structural components of the studied object should be assessed in detail at the early stages of the development process. This step does not demand special preparation, but gives valuable insights into the dynamics of the system. The results should use to balance the decision-making process by controlling extremely influential factors, able to push the adaptation plan towards their preferred targets. It is also a good tool for the detection of maladaptation preconditions and potential affected parties. This is seen from the factors and components of the system, which are most affected by others and thus more prone to give unexpected effects. By performing system impacts analysis one creates better ground for designing efficient responses to climate changes. Life cycle assessment should be applied to the

alternative chosen as the best one, so that any possible externalities would be taken to light and mitigated if possible or managed via modification of the adaptation plan. Most practitioners stress the need to evaluate adaptation plans in as many temporal perspectives and possible, and thus short, medium and long-term overview of the adaptation plan development must be done using expertise available among the working group and outside. The role of design thinking in prevention of maladaptation was stressed by experts and its role is crucial at both ends of the development process: at the beginning to create an efficient adaptation plan and at the end – to check the correspondence of the plan to the principles of good design. Consideration of maladaptation examples provide a good background to build on, enabling avoidance of the adaptation pathways, which have already proved to be inefficient.

It is also a good start for brainstorming ideas directly opposite or modified as compared to those leading to maladaptation. In many cases it is good to split the area, considered for adaptation into functional facies – derived from geology this term covers any part of a unity, which possesses a certain set of attributes making it distinct from other parts. In the given context functional facies would represent a unit of a system “city – climate effects”. The dividing principle may be of any kind and besides the obvious land use units, it is possible to deduct based on stakeholders, environmental media types or components of urban infrastructure. Despite the seemingly complicated this approach is rather efficient, being based on the same framework it yields comparable results. The case study of the First Kyiv Machine-Building Plant was reconsidered accounting given recommendations. The rethinking of the project showed that it was enough to separate environmental pollution from climate issues to get different view of the benefits of suggested alternatives (Fig. 3).

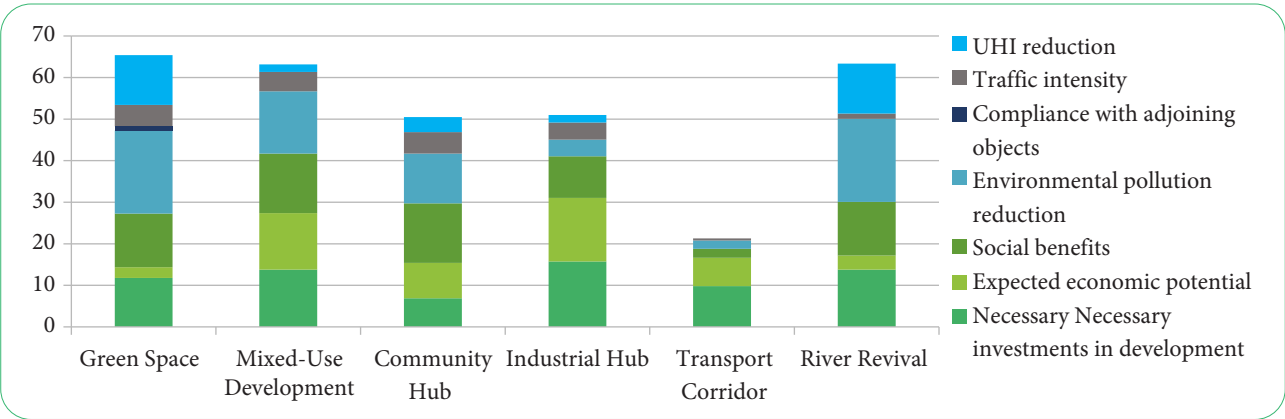


Figure 3. Comparison of the alternative development projects (reconsidered after maladaptation risks mitigation)
Source: created by the authors

As a result, even though “Mixed-Use Development” was preferred due to social and economic reasons, it would be outweighed by “Green Space” development and was equivalent to “River Revival”. The difference was

small but in a long-term perspective it would grow. This refusal from big developments in city centres is a sound pathway to climate resilience, because centres are the hearts of UHIs. The change is more clearly represented at

the step of impact interaction analysis: impact matrices show factors division into those that cause changes in the system and those which change under the combined pressure of other. It is also the reflection of driving forces of

the system status: one can clearly see which factors should be dealt with to bring dynamics to the system and which component is a receptor and will receive pressure of this dynamics (Fig. 4-5).

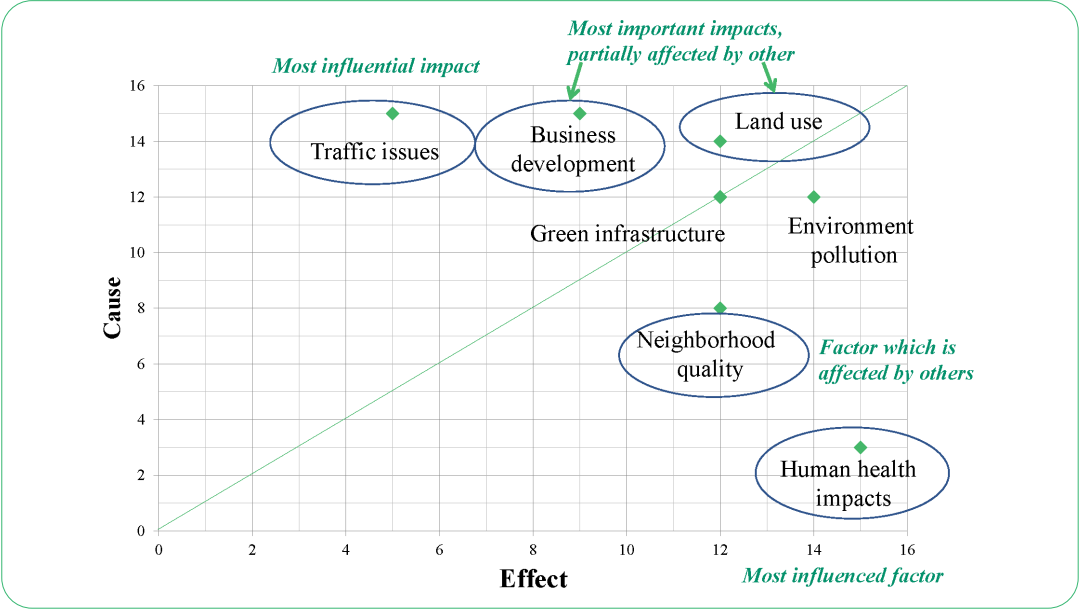


Figure 4. Impact matrix for initial consideration of system drivers

Source: created by the authors

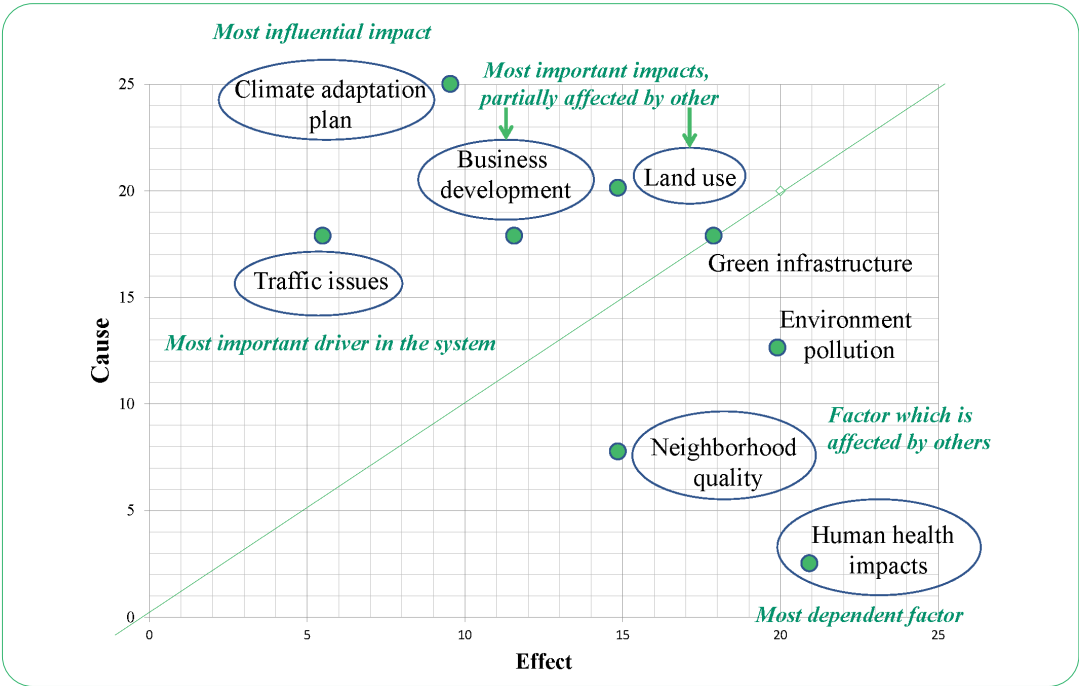


Figure 5. Impact matrix with separated climate factor

Source: created by the authors

The same amendment to the matrix (separation of environmental and climate change issues) slightly changed the relative position and roles of the factors, but climate adaptation plan and its implementation turned to be at the

dominant position. Climate adaptation was shaped by the land use and business development, but it was definitely the factor which set frameworks for business and land use as well as all other factors in the system. Another important

insight was traffic issues factor: it appeared to be as one of the major sources of all problems in the area and a constraint for any alternative, limiting room and opportunities for any development or adaptation. It was also one of the reasons for UHI origination, deepened by climate effects. Thus, traffic issues factor is indeed the one which should be dealt with before any adaptation plan gets chance to be efficient. Green infrastructure occupied central position in the impact matrix, which means that any interventions in this component would affect others and was at the same time limited by influential factors. Nature-based solutions are often seen as the best approach in adaptation, being such, but it was shown that they were still able to produce externalities and should be considered in details as well as technical and organisational solutions.

Developing action plans to tackle climate raised problems is a type of work, which is in great demand, but lacks comprehensive background in terms of mitigating risks of failure. It is already known that considering local conditions is a decisive component for the successful adaptation, but it is not enough to know the problems and resources. The analysis of maladaptation cases is important for the systemic understanding of the problem and the designing experience is necessary to engage creativity and innovative approaches into the process. Maladaptation is caused by many reasons, many of which are not understood until the onset of the problem. The effects of maladaptation are spread over various affected groups and might be of different scales; this highlights the need to conduct systematisation and vigorous analysis of the known case, collect additional data about them and work on their classification and causation substantiation. Having learned the roots of such failures, more efficient plans of adaptation will be developed.

There is also a clear lack of adaptation components in the urban development plans and projects of post war reconstruction are in the area of great risk of being inefficient, since they are developed within minimal time periods and often without experienced specialists among the project teams. Development of consistent framework for the analysis of project solutions will be helpful in making them maladaptation-proof and highly efficient. However, adaptation can be well-planned at the moment of plan approval, and then fail because of dynamic nature of climate change effects themselves and new issues, raising on the way of actions implementation. Accepting the impossibility to prepare to all possible challenges, the authors still see the need for design thinking to be important tool in preparing ground for adapting the plan itself to addressing the unexpected problems.

✓ Discussion

Design thinking method has historically been much used in solving complex, changing, disputable issues of the interested parties in an integrated way. M. Zeltina (2021) previously showed that despite well-developed strategy, principles and great potential in achieving sustainable development goals, design thinking is little integrated

into sustainability science and planning. L. Shi & S. Moser (2021) indicated that local players were able to develop good adaptation plans without national leadership, but this would be possible if members of the action group possessed the design competences. There is a strong belief that the most important thing is to start doing something in response to climate changes, and that it will be a better situation than if nothing is done. But as multiple examples have shown there is a risk of exacerbating climate induced problems and pushing communities into even harder pressure of climate change effects to the extent when there is no way out. Thus, E.L.F. Schipper (2020) argued that maladaptation is just one of possible outcomes of adaptation actions with the likelihood sometimes equivalent to the positive results. Broadly, they stem from institutional, infrastructural and behavioural issues and there is a specific combination of causes for failure in each case. The outcomes could be different and following the patterns, described by A.E. Piggott-McKellar *et al.* (2020) strong evidences for rebound maladaptation were seen in the alternative chosen at the first stage. Moreover, projects of urban development are very vulnerable to shifting maladaptation (Neset *et al.*, 2019), or are able to cause negative externalities (Antoci *et al.*, 2022). The resulted best option seems to be opposite to the essence of the urban development, but degrowth strategy is gradually getting more research support in many systems, as it was shown by A. Zango-Palau *et al.* (2024) for mountain regions.

Enough time has already passed since the beginning of adaptation programmes initiation and implementation, and the analysis of the outcomes can be conducted and not only monitor progress. However, accumulated data on maladaptation has not provided a sound basis for their avoidance and the uncertainty of adaptation plans is still high. This makes research on the maladaptation preconditions important for developing principles of their avoidance. In line with four structural challenges that contribute to maladaptation, defined by A. Bertana *et al.* (2022), the above presented recommendations insist on the need in holistic approach and setting priority on adaptation equal to economic and social considerations. Furthermore, qualitative assessments should be approached as a separate and valuable framework, for which MCE was offered as a good option for partial quantification without losing valuable information.

Among the major problems of national and local adaptation plans S. Juhola & J. Käyhkö (2023) noted the lack of well defined metrics for measuring adaptation failure. This was also highlighted by K. Findlater *et al.* (2023), who formulated the need for a values-based approach to both adaptation and maladaptation in order to grasp all the diversity of factors, affecting the system of climate adaptation. Urban areas represent a specific case of adaptation issues as compared to vast natural zones suffering from changing living conditions. H. Bulkeley (2021) pointed that urban areas undergo the cascade effects of so many complex and intertwined consequences, that it turned into personal problems of urban residents. However, many authors, in particular

A. Hurlimann *et al.* (2021) argued that adaptation is still not fully embedded into urban policy documents. Moreover, A. Otto *et al.* (2021) revealed the gap between mitigation and adaptation efforts, when some cities dived into mitigation initiatives and neglect adaptation or vice versa, – this should be also considered an element of maladaptation.

Urban areas adaptation has its peculiarities, which might give a help in developing adaptation. Some cities across the globe have a range of similar attributes and problems caused by climate changes as well as possible solution might fit cities located at great distance from each other. Urban budgets are stronger and thus able to support quite expensive projects and not chase profit out of climate adaptation interventions. Nongovernmental and other civil groups are more developed and active in cities, and ready to participate in the process, but this raises the importance of collaboration planning and makes it a separate task of the process. At the same time, all projects will have to fit into compact and often complicated structure of a city. Thus, urban areas are about to dramatically increase demand for adaptation plans and these plans must be very specific to avoid maladaptation.

Some researchers have already developed and presented frameworks for the assessment of adaptations efficiency. Being unexpected in essence, maladaptation could be predicted based on the analysis of prerequisites, which have been defined primarily for agriculture, forestry and water resources management. Just like the given research, L. Wiréhn *et al.* (2018) noted considerable gaps in understanding adaptation regularities, which must be filled in project teams before the initiation of adaptation plan design process. Following B. Boutroue *et al.* (2023), it is important to develop competences of the governance of adaptation projects, since there would always be need for compromises between multiple needs and stakeholders. C. Singh *et al.* (2021) offered 11 guiding principles for adaptation monitoring and evaluation, which could be used to define signs and harbingers of maladaptation, though quite general: lack of equality, low economic feasibility and deficient consideration of local interests. However, it is impractical to concentrate efforts on observations rather than trying to avoid maladaptation drivers at the very beginning – design and development stage. Except a chance to reduce the risks of maladaptation, concentration on improving adaptation design enables separation of inadequate planning from inefficient implementation.

The review of the available conceptual frameworks for maladaptation evaluation by C.-F. Chi *et al.* (2021) concluded that only precautionary framework and assessment framework can be used to prevent maladaptation in the initial planning stage of adaptation. These frameworks contain guidelines and checklists to control the process of design in a way that avoids exacerbating the risks of maladaptation. However, these frameworks cannot detect maladaptation caused by improper implementation of adaptation plans. There is still a range of complications omitted by formal frameworks, since they work with what has

been produced at the design stage. But adaptation can be compromised by dynamic nature of changes themselves, varied local conditions, side effects of climate changes and evolution of social and economic situation, independent from environmental processes.

Under such pressure adaptation design process must possess the following characteristics: creative – each case/place/community is specific and there are no solutions fitting everyone; flexible – plans must have “room” for customisation and be able to change in response to new conditions during design and, what is even more important, during implementation; innovative – there are very few analogues and reliable predictions of success is uncertain; intrinsic – must be embedded in all pathways of development of the area and community in question; looking inside – climate changes are not external to communities, they are part of their life and must be viewed in this way and any adaptation should match local cultural and social landscape; prudent – able to meet demands of the future situation; environmentally and socially friendly. These attributes raise the need for the development of design thinking competences in members of multidisciplinary working groups, which are usually created for the development of adaptation plans.

✓ Conclusions

The risks of maladaptation represent a serious problem for building resilience of urban areas, especially in development initiatives. The project of the abandoned industrial site development in the Kyiv was analysed to single out factors, contributing to the choice of alternative, being a potential maladaptation. The post-rehabilitation alternative for the First Kyiv Machine Building Plant chosen using the method of multicriteria evaluation by the student-expert group was “Mixed-Use Development” project. But it had a high likelihood of leading to rebound and shifting maladaptation, as well as negative externalities. The recommendations on the reduction of the maladaptation probability were developed and delivered to the project group. The reconsideration of the project alternatives after design thinking training and accounting recommendations using the same methodology resulted in the rethinking of the best alternative towards the one which would limit the economic development of the area in favour of “Green Space” or “River Revival”.

The application of MCE methodology has also demonstrated the importance of separating the target of climate adaptation from all other aims pursued by the development projects. An important insight of the research is the revealing the importance of the impact interaction analysis: impact matrices were able to display the difference in the considerations of various factors, involved in the choice of the best alternative and their real impact-effect ratios. The outcomes of the analysis have highlighted the importance of beginning adaptation projects with a holistic perspective, although each problem needs specific details for actual evaluation. There is still no universal

approach to mitigation of maladaptation risks and these research result can make a contribution to the development of such framework. The next step of the study would be the elaboration of parameters and criteria for evaluation of maladaptation probability and significance. Additionally, there is a need for regular rethinking of concepts, since adaptation is evolving, just like maladaptation. Current trend is to shift from building resilience and keeping the balance in urban ecosystem towards the capacity

of continuous transformation of resilience. Therefore, it would be necessary to study the maladaptation as a process instead of an outcome of it.

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✓ Conflict of Interest

None.

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Дизайн-мислення для уникнення дезадаптації при формуванні стійкості міст до зміни клімату

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✔ **Анотація.** Адаптація населених пунктів до наслідків зміни клімату є актуальним завданням для науковців та численних стейкхолдерів, зацікавлених в ефективному функціонуванні міських систем та безпеці мешканців. Розробка планів адаптації ускладнюється через відсутність визначеності щодо результатів цих дій. З іншого боку, вже наявні дані про численні випадки дезадаптації, тому дане дослідження було спрямоване на визначення принципів адаптаційного планування, які допомагають уникнути ризиків дезадаптації. На прикладі спільного проекту з реабілітації занедбаного промислового об'єкту в центрі Києва, Україна, розробленого магістрантами з Канади, Ісландії та Латвії, проаналізовано чинники дезадаптації та запропоновано принципи ефективної імплементації кліматичної адаптації в ініціативи з розвитку міста. Метод багатокритеріальної оцінки використано для порівняння можливих пост-реабілітаційних проектів та визначення ролі окремих факторів у підвищенні ймовірності дезадаптації. Вагомість факторів, що впливають на вибір альтернативи, встановлювалася зі залученням проектувальників, фахівців, які мають досвід розробки планів адаптації, громадських організацій та науковців. Розроблено рекомендації щодо зменшення ризиків дезадаптації при розробці планів адаптації, які були використані для перегляду результатів спільного проекту та відмови від альтернативи, схильної до дезадаптації. Показано, що кліматичні питання слід розглядати як окрему категорію і ціль, замість того, щоб включати їх у широкую категорію охорони навколишнього середовища. Оцінка підкреслила важливість дизайн-мислення та аналізу системних зв'язків об'єктів проектування для мультидисциплінарних команд, які працюють над плануванням розвитку міста з урахуванням заходів з адаптації. Результати дослідження можуть бути застосовані для підготовки проектних груп, які працюють над розвитком міст та післявоєнною відбудовою, щоб гарантувати ефективну реалізацію потреб та перспектив адаптації до зміни клімату у відповідних планах

✔ **Ключові слова:** багатокритеріальне оцінювання; міський розвиток; експертна оцінка; охорона навколишнього середовища; адаптація до змін клімату



Analysis of anthropogenic transformation of the hydrographic network in the northern part of Lviv according to cartographic sources

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✓ **Abstract.** The emergence of new and densification of existing urban spaces in Lviv leads to anthropogenic transformation of the hydrographic network. The purpose of the study was to analyse the degree of transformation of water objects in the northern part of the city based on cartographic sources. The study covered the northern part of Lviv, the town of Dublyany, the villages of Malekhiv, Velyki Hrybovychi, Zbyranka and Murovane. The study of water bodies was carried out with topographic maps of the scale range from 1:25,000 to 1:100,000, which made it possible to cover a time period of more than 240 years. Clear trends to decrease the length of open channels, the number of tributaries and the water content of the Holoskivskyy, Zboivskyy and Malekhivskyy streams, which is due to both natural and anthropogenic factors had been marked. The length of the natural channel of the Holoskivskyy stream decreased from 4.7 to 0.9 km, the Zboivskyy stream – from 5.2 to 3.2 km, and the Malekhivskyy stream – from 7.9 to 5.3 km. The largest number of ponds (15 units; 10.3 hectares) on streams was found in the second half of the 18th century. Subsequently, a decrease in both the number and area of ponds was observed. The lowest figures fall on the interwar Polish period, when only four ponds with a total area of 2.5 hectares were recorded. During the Soviet period, the number and area of ponds increased slightly (9 units; 4.6 hectares) and reached the level that existed in the second half of the 19th century. There were 14 water mills operating on most of the ponds of that time located in the villages of Holosko Velyke, Zamarstyniv, Zboyishcha and Malekhiv. After that, the number of mills steadily decreased: at the beginning of the 19th century – nine; in the second half of the 19th century – seven; in the interwar period – five. After the World War II, the operation of all water mills was stopped. The conducted analysis of the degree of transformation of the hydrographic network is aimed at correcting the development plan of the northern part of the city and implementing the environmental management system

✓ **Keywords:** hydrographic network; stream; river bed; pond; topographic map

✓ Introduction

The issue of protecting and preserving watercourses and reservoirs in Lviv and its agglomeration is crucial for environmental, social, and economic reasons and involves maintaining biodiversity and landscape diversity, providing

water to the population and economy, regulating the microclimate, creating recreational opportunities, etc. Water bodies in regions where there is a shortage of surface water are becoming important. Taking into account global

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climate changes, terrain features and watershed locations, Lviv belongs to such a region itself. In fact, the entire hydrographic network of the city is hidden in collectors, and there are no large water bodies within its boundaries, which is why the watercourses and reservoirs that remain in the city or are located within the Lviv agglomeration are of particular value to residents. In view of this, any measures and steps related to the restoration, preservation and protection of water bodies within Lviv and its agglomeration are of great importance.

The issue of anthropogenic transformation of the hydrographic network has been considered in many publications, in particular, the problems of economic impact on water bodies are discussed in the paper by V. Andreev *et al.* (2021). Geoecological studies of river basins are described in the works of L. Tsaryk *et al.* (2020) and I. Khomiak *et al.* (2022). In this study, the main aspect of the description of the study area is focused on the Holoskivsky, Zboivsky, and Malekhivsky streams, which belong to the basin of the main river of the city, the Poltva. These streams operate under specific conditions, as the Main European Watershed, which divides the Baltic and Black Sea basins, runs through the upper reaches of their basins. The analysed streams have similar conditions for the formation and development of their valleys and floodplains, but differ in the level of their anthropogenic transformation. The studied streams are located in the basin of the transboundary Western Bug River, which is heavily transformed and polluted in the study area (Khilchevskyi *et al.*, 2018), in particular due to the Poltva tributary, which is the main collector of Lviv (Kurhanevych & Shipka, 2020). The features of the construction and operation of this collector are described in the monographic work of O. Karelin (2021). As of 2024, most of the water bodies in the study area are in unsatisfactory hydroecological condition, are heavily polluted, and require channel cleaning and a number of optimisation measures aimed at complying with the Water Code of Ukraine (1995) and establishing the boundaries of coastal protection strips of 25 m in width.

Cartographic materials serve as the basis for studying the conditions of formation of natural landscapes and the degree of their anthropogenic transformation. To recreate a retrospective of the dynamics, development, and consequences of natural and anthropogenic processes in the studied area, cartographic sources from different historical periods are important. They should be used to analyse the location, current state, and development of natural and economic systems, and to study the place names of geographical objects of the time. Researcher E. Ivanov (2018; 2019) has accumulated experience in retrospective geographical research using topographic (cadastral) maps of different time periods on a scale from 1:25,000 to 1:100,000. The use of cartographic information involves solving various technical issues related to the determination of the scale of topographic maps for the values of hydrological parameters of the river network, as in A. Selehiev *et al.* (2023), and

the analysis of morphometric parameters and the design of thematic maps using a raster geoprocessing tool, as in H.S. Çadraku (2022). The historical cartographic sources of Lviv and their interpretation should also be focused on. Among the reviews, attention should be paid to publications that analyse topographic maps and plans of Lviv in various historical sections – from Austrian to Soviet (Sossa, 2020). However, most historical maps and plans of the city do not cover the study area, so the purpose of this work was to conduct a comparative analysis of the degree of anthropogenic transformation of water bodies and to outline their hydroecological status.

✓ Materials and Methods

An area covering the northern part of Lviv was selected for the hydrological and hydroecological study, as well as the settlements of the Lviv City Territorial Community bordering it from the northeast – the town of Dubliany, the villages of Malekhiv, Velyki Hrybovychi, Zbyranka, and Murovane. In June 2024, a field survey of the study area was conducted to determine the current state and degree of anthropogenic transformation of the hydrographic network in the northern part of Lviv. The survey included an inspection of the state of water bodies, determination of their hydrological parameters, water sampling and photographic recording. At the same time, local residents were interviewed, and their assistance was provided in finding the remains of some watercourses and reservoirs. This made it possible to clarify map information that has not been updated for more than 30 years.

The scale of the study was chosen for analysing various cartographic geodata. The study of the conditions of emergence and formation of modern landscapes in the northern part of Lviv was carried out on the basis of topographic maps of the scale of 1:25,000-1:50,000. The historical and cartographic collections of the Cabinet of Cartography of the Vasyl Stefanyk Lviv National Scientific Library, the Central State Historical Archives of Ukraine in Lviv, and various online cartographic sources (Lomnicki, 1899; Arcanium maps, n.d.; Military Geographical Institute..., n.d.; Topographic maps..., n.d.) were studied. The topographic maps of the appropriate scale for five retrospective geographical periods (individual topographic surveys, metrics) were selected, which allowed to cover a chronological period of more than 200 years (from the second half of the 18th to the second half of the 20th and early 21st centuries), in particular: Austrian maps of the First Topographic Survey (1779-1783), scale 1:28,800; Austrian maps of the Second Topographic Survey (1819-1820), scale 1:28,800; Austrian maps of the Third Topographic Survey (1869-1887), scale 1:25,000; Polish maps of the Military Geographic Institute (1929-1939), scale 1:25,000; Soviet maps of the General Staff of the USSR (1968-1989), scale 1:50,000. According to the regulation on the use of cartographic data, which was exacerbated during the Russo-Ukrainian War, there is a ban on publishing a more detailed scale.

The choice of cartographic materials has led to the need for relatively equal time intervals between topographic surveys, which in this case is 40-60 years. The first topographic surveys occurred during the period of the Austrian Empire, which accompanied the cadastral metrics (land surveys) of the studied territory. Based on these metrics, the first maps suitable for retrospective geographical analysis were compiled. Interwar Polish and postwar Soviet maps were also relevant for this analysis, as they were similar in scale and in the way they depicted the topographic situation. To enhance the interpretation of the cartographic materials, sheets of other topographic maps were used: Austrian, scale 1:75,000 (1890s); interwar Polish, scale 1:100,000 (1920s-1930s); Soviet, scale 1:100,000 (1990s).

At the same time, cartographic works on the studied territory from other countries and time periods were analysed, which turned out to be unsuitable for retrospective geographical analysis of the anthropogenic transformation of the hydrographic network in the northern part of Lviv. Topographic maps for different historical periods compiled by the military topographic departments of the Russian Empire, Germany, and the United States were used. The selected maps are compilation maps, built using the topographic foundations and cartographic information of the above-mentioned Austrian and Polish maps of previous

time periods. Materials from the period of World War II at a scale of 1:100,000 were used, namely German (1939) and American (1944) topographic maps. The Google Maps (n.d.) and Geoportal of Lviv (n.d.) mapping web services were used to clarify the current information on water bodies. However, these mapping resources lack a unified understanding of the location of water bodies in the city.

✓ Results and Discussion

The Austrian maps of the First Topographic Survey, which are more than 240 years old, show an extensive network of watercourses that originate near the Main European Watershed and drain their own water into the Poltva (Western Bug River Basin). The study area is sloping from west to east, namely from the Roztochia uplands to the complex structure of the Pasmove (Hriadove) Pobuzhzhia, which is characterised by raised ridges and wide valleys. This slope determined the general direction of flow of all the studied watercourses, which have a clear northwest-southeast direction, mainly towards the wide Poltva River valley. The Malekhivskyy stream is mapped as a third-order watercourse, while the Holoskivskyy and Zboivskyy streams are mapped as second-order. It is possible that these streams were also classified as third-order watercourses, but this is not reflected on the topographic map (Fig. 1).

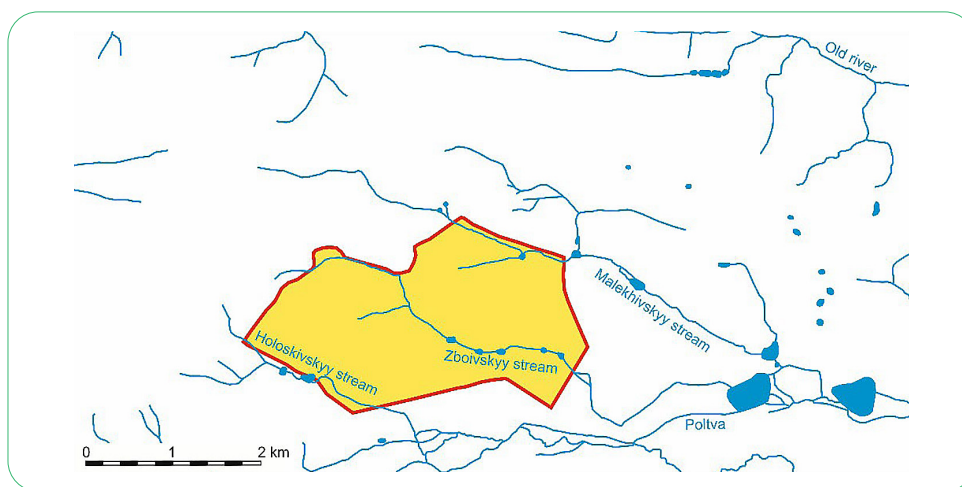


Figure 1. Anthropogenic transformation of water networks in the study area based on the analysis of the Austrian map of the First Topographic Survey (1779-1783)

Source: created by the authors

The oldest cadastral map is informative, showing geographical objects that reveal the water management activities of the time. The Holoskivskyy stream has two large (1.0 hectares each) and one small pond with water mills, as well as three dams with drained reservoirs. In Zamarstyniv, there are two flow-through mills on the stream. There are five small ponds on the Zboyishchia stream in the Zboyishchia Village, all with water mills. Four different-sized ponds with water mills and two more dams on drained reservoirs were found on the Malekhivskyy stream. The largest of

them was the one with an area of more than 3.0 hectares. Thus, watercourses and reservoirs played an important role in the economy of the villages of Holosko Velykyi, Zamarstyniv, Zboyishcha, and Malekhiv.

The analysis of the Austrian maps of the Second Topographic Survey reflects the situation in the first half of the 19th century. This topographical map shows the network of watercourses in better detail and shows its branching down to the source. In this case, the studied streams are mapped as third-order watercourses (Fig. 2). As for the

number of ponds, it has increased to six ponds at both Holoskivskyy and Zboivskyy streams. Most of them housed water mills. No ponds were recorded on the Malekhivskyy stream during this period. The stream channels continue to be open along their entire length, are natural in nature and travel moderately through the valleys, and the presence of a significant number of ponds indicates that they are full of water. Stream valleys determine the

structure of settlement in suburban villages. The extent of anthropogenic transformation of water bodies in the second half of the 19th century is shown on Austrian maps of the Third Topographic Survey. Based on this topographic map, it can be argued that the order of the Holoskivskyy and Zboivskyy streams has been reduced to the second order, while the Malekhivskyy stream remains a third-order watercourse (Fig. 3).

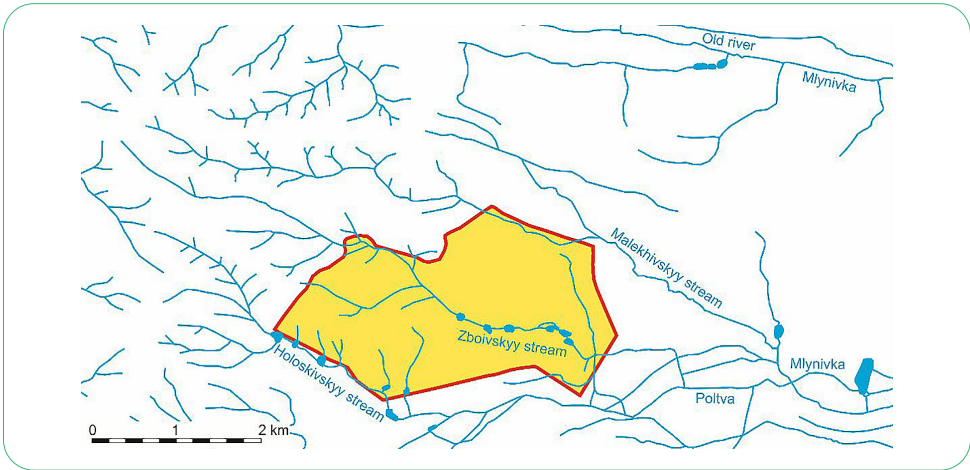


Figure 2. Anthropogenic transformation of water networks in the study area based on the analysis of the Austrian map of the Second Topographic Survey (1819-1820)
Source: created by the authors

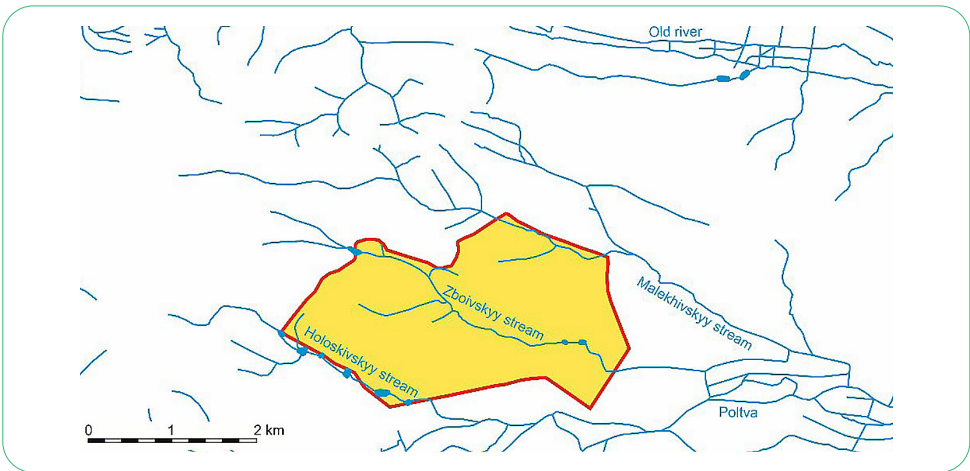


Figure 3. Anthropogenic transformation of water networks in the study area based on the analysis of the Austrian map of the Third Topographic Survey (1869-1887)
Source: created by the authors

This may indicate a certain decrease in the water content of the studied streams and the loss of some small tributaries. Six ponds with water mills continue to operate on the Holoskivskyy stream, in the villages of Holosko Velykyi and Zamarstyniv. The area of the largest ponds does not exceed 0.8-1.0 hectares. Another mill is located at the confluence of the stream with a separate branch of the Poltva River, which is labeled Mlynivka. The area in this neighborhood is called Stavky. In the Zboyishcha Village, the ponds are disappearing, and the only pond (0.8 hectares)

in the valley of the Zboivskyy Stream is located in its upper reaches, in an area similarly named Stavky. In the valley of the Malekhivskyy stream, upstream from the Malekhiv Village, there is a water mill that operates at the speed of the stream's tributary.
In the early 20th century, Austrian topographic maps were updated to a scale of 1:75,000. Despite its smaller scale, they are highly informative. The number of water mills on the Holoskivskyy stream has been preserved, and one mill and several small ponds on the Zboivskyy

stream have been restored. On the other hand, no ponds or mills are registered on the Malekhivskyy stream. The natural and geographical patterns of the emergence and development of modern landscapes in the northern part of Lviv are associated with the formation of watercourse floodplains, which is well reflected on the map of quaternary sediments (Lomnicki, 1899). This map was created on the basis of the previously discussed topographic base. The valleys of watercourses are composed of alluvial deposits (sands, sandy loams), their width is not significant (up to 100 m), and in the lower part they widen slightly

(up to 200-250 m). The lower part of the streams ends in the wide valley of the Poltva River.

It is worth considering the interwar period on the basis of Polish topographic maps of the Military Geographic Institute. The analysis of these maps allowed to identify a significant reduction in the number and shallowing of watercourses, which is associated with the intensification of agricultural development of the suburban areas of Lviv. The Malekhivskyy stream has become a second-order watercourse, while the Holoskivskyy and Zboivskyy streams are first-order streams that do not receive any tributaries (Fig. 4).

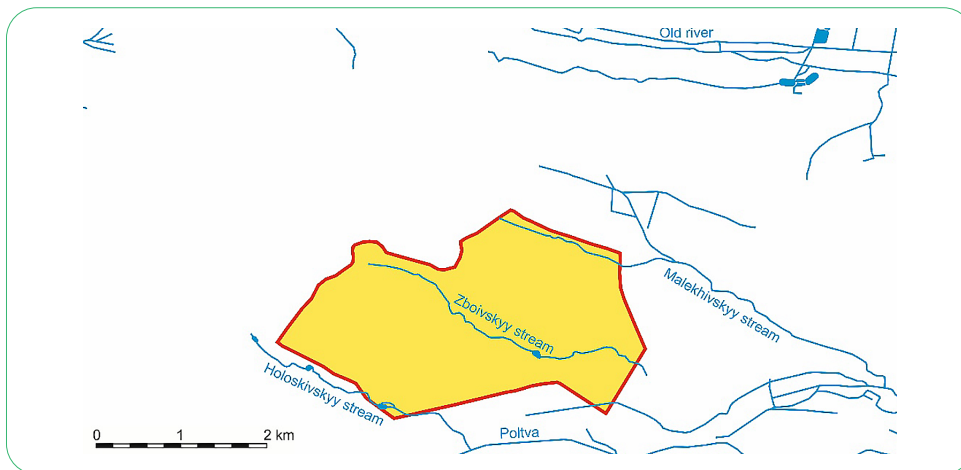


Figure 4. Anthropogenic transformation of water networks in the study area

based on the analysis of the Polish topographic map of the Military Geographical Institute (1929-1939)

Source: created by the authors

At the same time, the Zboivskyy stream is lost just beyond the Zboyishchia Village, in the swampy Poltva valley. It is likely that the stream could not be investigated and flows into the Poltva downstream. At the same time, there is a significant reduction in the length of watercourses and a decrease in the number and area of ponds. Only three small ponds remain in the valley of the Holoskivskyy stream and one on the Zboivskyy stream. The only operating water mills (5 units) remained on the Holoskivskyy stream. At this stage of changes to the water supply network in the northern part of Lviv, the riverbeds in some areas were turned into underground or reclamation channels, and most of the ponds disappeared. In the early 20th century, the level of urbanisation increased and the water content of the city's rivers decreased. They were no longer able to transport suburban wastewater and began to turn into dirty ditches.

Polish topographic maps at a scale of 1:100,000 largely do not confirm the information from detailed topographic maps of the same period. There was an error in the mapping of the Holoskivskyy stream – it is not shown in the upper reaches, although water mills along the valley are marked. The Zboivskyy stream is classified as a second-order watercourse. The number of registered ponds also differs: two on the Holoskivskyy stream; five on the Zboivskyy stream; and one on the Malekhivskyy stream. The map also shows

one water mill each on the Zboivskyy and Malekhivskyy streams. These inconsistencies may also be due to the borrowing of data from a previous Austrian topographic survey. During the World War II, two separate cartographic documents were created in Germany and the United States on the basis of Polish topographic works. Although these topographic bases are composite, hastily made, the way they are presented makes it possible to analyse the features of the valleys of the studied streams and to clarify the features of the hydrographic network during this period.

The retrospective geographical review of cartographic information was concluded by analysing topographic maps of the Soviet period, which reflect the situation as of the 1980s and 1990s. On topographic maps at a scale of 1:50,000, all watercourses are divided into natural and artificial (canals) streams. In particular, the open channel of the Poltva River then started from I. Mykolaichuk Str. During the development of the northern part of Lviv, the higher sections of the Poltva were sewered into the city's main collector. Intensive development also necessitated the sewerisation of the lower part of Holoskivskyy stream, which was caught in the dense urban development. There are two ponds in the open stream area, the largest of which is Stosyk Pond (0.9 hectares). In the lower part of the Holoskivskyy stream valley, two artificial reservoirs are depicted, which are practically connected with river activity. The open channel of

the Zboivskyy stream begins at the beginning of the quarter along Shchurat Str. and continues to flow along the Zboishchy District and under the bridge near the modern Halytskyi crossroads, and flows into the Poltva drainage canal system. A pond (0.6 hectares) is shown at the head of the stream, which was already diverting water to the collector. There was also a small pond on the stream not far from the Emergency Hospital. The Malekhivskyy stream underwent the least changes, its channel to the E372 (M-09) Lviv-

Rava-Ruska Hwy. remained virtually unchanged with three small ponds. Due to the loss of water content in the upper reaches, the flow is shown as intermittent (seasonal). Below the road, the channel is partially canalised and receives a tributary with an extensive system of drainage channels, which closely fits and continues to drain infiltrates from the liquidated Hrybovychi landfill as of 2024. In general, the order of the studied watercourses has not changed compared to the previous mapping (Fig. 5).

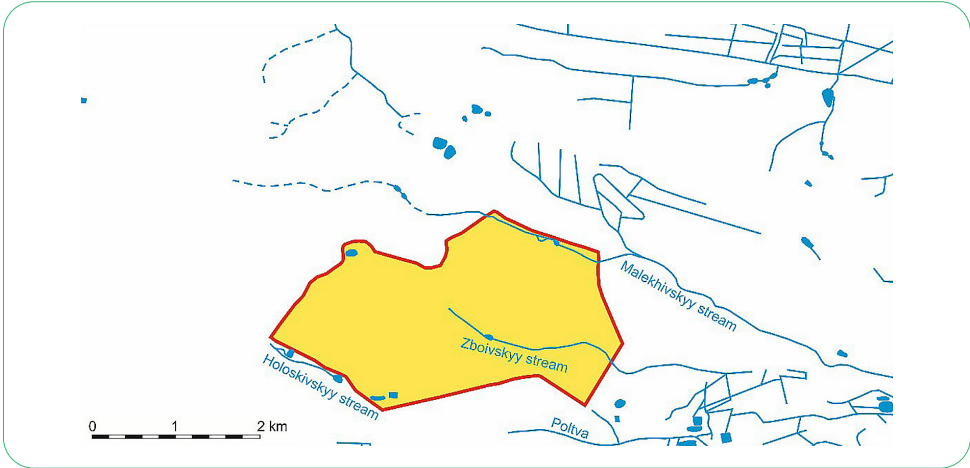


Figure 5. Anthropogenic transformation of water networks in the study area based on the analysis of the Soviet topographic map of the USSR General Staff (1968-1989)
Source: created by the authors

The Soviet period played a crucial role in the transformation of Lviv’s waterways. During this period, the city’s territory expanded significantly. Changes were particularly intense in the new neighbourhoods, where new residential and industrial districts were built. Large-scale work to block open streams in the northern part of Lviv was carried out in the 1970s and 1980s. Accesses to the middle and lower reaches, as well as to new construction sites, have been closed. Some springs, small ponds, and remnants of natural streams in park areas up to 1.0-1.5 km long remain. The beds of most watercourses were then filled up or hidden underground in collectors. According to G. the Poltva tributaries are piped over longer stretches: Holoskivskyy stream – 3.2 km, Zboivskyy stream – 0.6 km. Underground channels are also used for wastewater disposal.

Information from Soviet topographic maps at a scale of 1:100,000 is very generalised and duplicates data from more detailed topographic maps. The only difference is the

presence of a pond on the Zboivskyy stream, in a downstream location. It is worth noting the increase in the length of watercourses in the Poltva and Yarychivka valleys (Yarychivka Canal), which is due to their drainage and canalisation. And the emergence of a large number of sedimentation ponds in the area of active operation of the Lviv sewage treatment plant and infiltration ponds at the Hrybovychi landfill.

Based on the review of the mapping information, the main hydrological parameters of the hydrographic network of the study area were measured, which are shown in Table 1. The analysed parameters include the length of the open part of watercourses. In the absence of their image on the topographic map, it was understood that the stream was in a collector or that there was no information. The number and area of ponds and the number of water mills were recorded, which gives an indirect idea of the water content of watercourses and their water use.

Table 1. Hydrological parameters of the hydrographic network of the study area

Parameters of watercourses and reservoirs Topographic maps	Length of the open part of watercourses, km			Total number of ponds, units	Total area of ponds, hectares	Total number of watermills, units
	Holoskivskyy stream	Zboivskyy stream	Malekhivskyy stream			
Austrian map of the First Topographic Survey (1779-1783)	4.7	5.2	7.9	15	10.3	14
Austrian map of the Second Topographic Survey (1819-1820)	5.2	7.5 ¹	9.9 ¹	12	7.7	9

Table 1, Continued

Parameters of watercourses and reservoirs Topographic maps	Length of the open part of watercourses, km			Total number of ponds, units	Total area of ponds, hectares	Total number of watermills, units
	Holoskivskyy stream	Zboivskyy stream	Malekhivskyy stream			
Austrian map of the Third Topographic Survey (1869-1887)	5.1	5.4	7.6	8	4.7	7
Polish map of the Military Geographical Institute (1929-1939)	3.4	4.2 ²	5.3	4(8) ³	2.5	5(7) ³
Soviet map of the USSR General Staff (1968-1989)	0.9	3.2	5.3	9	4.6	0

Notes: ¹ – length of watercourses with a gully and beam network; ² – it is possible that the length is longer; ³ – data based on a Polish topographic map of the Military Geographic Institute at a scale of 1:100,000

Source: created by the authors

The cartographic works of different years differed in the way they were constructed; nevertheless, there is ample evidence to outline the trends of anthropogenic transformation of the hydrographic network over the past 240-250 years, so it is worth summarising them in accordance with Table 1. The main parameter of the negative processes that have occurred with watercourses in the northern part of Lviv is the reduction in the length of their open part. The length of the open part of the Holoskivskyy stream decreased from 4.7 to 0.9 km (5.2 times), the Zboivskyy stream from 5.2 to 3.2 km (1.6 times), and the Malekhivskyy stream from 7.9 to 5.3 km (1.5 times) (Fig. 6).

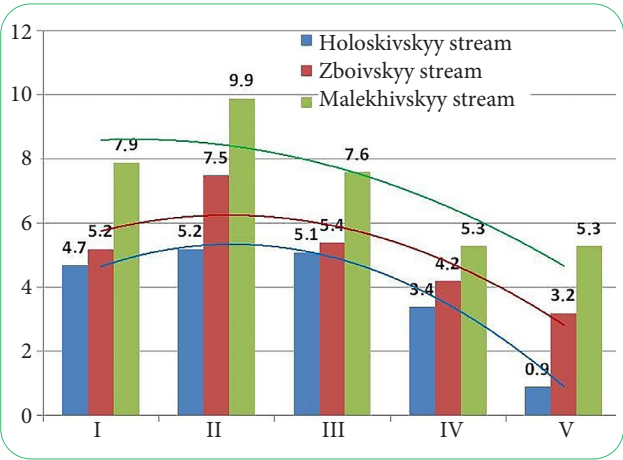


Figure 6. Length of the open part of watercourses in the study area in different retrospective geographical periods, km

Note: I – 1779-1783; II – 1819-1820; III – 1869-1887; IV – 1929-1939; V – 1968-1989

Source: created by the authors

If the maximum fixed flow lengths are taken, the ratios are changed to 5.8, 2.3, and 1.9 times, respectively. The intensity of hydrological processes also varied over time, so in the Austrian period it was balanced, and in the Polish and Soviet periods it was noticeable and accelerated. Already in the second half of the 19th century, there were trends of reducing the length of watercourses, which

intensified significantly with the beginning of the development of the northern part of Lviv and the increased anthropogenic pressure on the natural environment in the basins of the studied streams. The process of water reduction in the streams of the study area differed and led to different consequences for the management of the inhabitants. The number and area of ponds are self-sufficient indicators that illustrate the use of water resources in the study area. During the study period, these indicators changed significantly (Fig. 7).

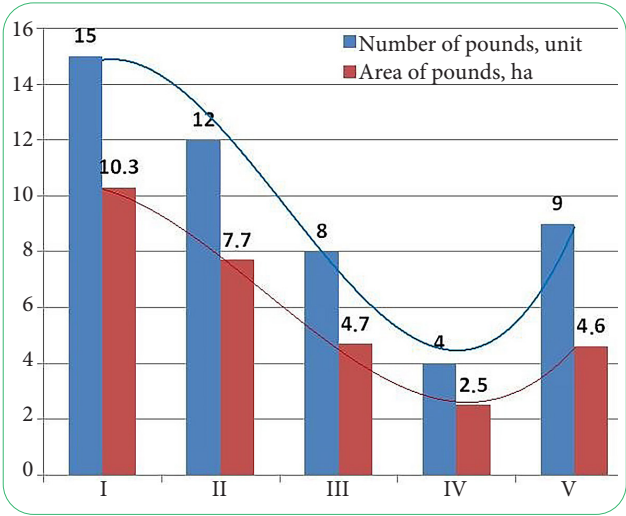


Figure 7. Number and area of ponds on the studied streams in different retrospective geographical periods

Note: I – 1779-1783; II – 1819-1820; III – 1869-1887; IV – 1929-1939; V – 1968-1989

Source: created by the authors

The largest number of ponds (15 units) on the studied streams was recorded in the second half of the 18th century. During this period, the largest area of water bodies was also observed – 10.3 hectares. In the following years, there was a gradual reduction in both the number of ponds and their area. The lowest figures are from the period of interwar Poland, when only four ponds with a total area of 2.5 hectares were registered. In Soviet times, the situation

improved somewhat, with the number of ponds increasing to 9 and their area to 4.6 hectares, which was close to the figures of the second half of the 19th century. The excessive and unjustified growth of water use in the Soviet period, in order to counteract the general trend of decreasing river water content and the rapid sprawl of the northern districts of the city, led to the depletion of the studied streams.

Most of the ponds of that time, located in and around the villages of Holosko Velykyi, Zamarstyniv, Zboishcha, and Malekhiv, had water mills. The existence of the mills testifies to the sufficient water availability of watercourses at that time, which were able to regularly fill the ponds and supply water flow energy for their operation. The proximity to Lviv necessitated a large number of water mills, so at the end of the 18th century their number was the highest (14 units). From this retrospective and geographical period, the number of mills steadily decreased: at the beginning of the 19th century – nine; in the second half of the 19th century – seven; in the interwar period – five (Fig. 8). After the World War II, all water mills were finally shut down due to the loss of water in the streams and the economic inexpediency of further operations.

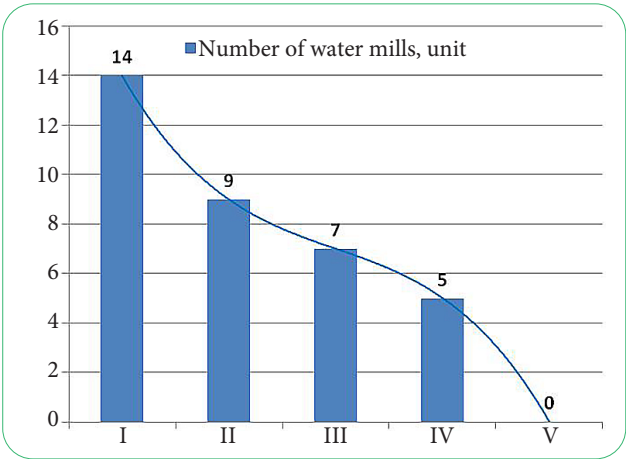


Figure 8. The number of water mills on the studied streams in different retrospective geographical periods
Note: I – 1779-1783; II – 1819-1820; III – 1869-1887; IV – 1929-1939; V – 1968-1989
Source: created by the authors

The Holoskivskyy stream remains the most abundant tributary of the Poltva in the northern part of Lviv. The natural channel has been conditionally preserved for a length of about 1.0 km. The watercourse was filled with springs; five springs were examined at its beginning and along the channel (100-150 m lower). The Zboivskyy stream is drying up, and the pond where it started has turned into a swampy area. This indicates the loss of power sources in the upper part of the stream. In its middle part, the largest anthropogenic transformational changes and sewerage were found. The Malekhivskyy stream is characterised by a similar situation with the current transformation of water bodies within the neighbouring Zboivskyy stream. Potentially, this

stream had a longer valley and higher water content, which it lost due to various natural and economic reasons. According to topographic maps of the late 20th and early 21st centuries, the length of the open part of the stream is 3.8 km.

As of 2024, almost the entire hydrographic network of the northern part of Lviv is hidden in collectors, and there are no large water bodies within the city, which is why the watercourses and reservoirs that remain in the city or are located within the Lviv agglomeration are of particular value to residents. In view of this, any measures and steps related to the restoration, preservation and protection of water bodies in Lviv and its agglomeration are of great importance for the formation of a new environmentally safe urban environment and the implementation of an environmental management system.

The evolution of river systems in the context of human activity has been a hot topic of research, discussion, and debate among geographers and hydrologists. The study of spatial and temporal changes in river systems was primarily related to the study of their structural transformation. The basis for the study of river systems was laid by R. Horton (1945). The researcher proposed a system of ordinal classification of flows and established a number of quantitative statistical regularities of their structure, which later became known as Horton's Laws. Many works have been devoted to the study of the ordinal classification of rivers. For example, S. Sarnavskyy *et al.* (2020) conducted a retrospective analysis by comparing the hydrographic network of these rivers in certain time frames to determine the nature and directions of changes in the river network of the Khorol and Govtva river basins (Dnipro River basin). Also, in the works of I. Kovalchuk *et al.* (2020) many questions in the study of river basins are devoted to the structural transformation of river networks. An interesting analysis is presented in the work of L. Carrao *et al.* (2020). The authors studied how geomorphology shapes the structure of river networks and, in turn, controls the variability of physical habitats and affects spatial patterns of biota. However, such studies have a significant margin of error because they cover large areas and usually use maps of different scales, which affects the accuracy of the research. Structural methods mainly focus on the static characteristics of river networks. They did not take into account changes in the river network, such as erosion, channel changes, seasonal fluctuations in water levels, etc.

Many studies of river systems are related to the study of their hydrochemical and geoecological state, these are the works of V. Khilchevskyy *et al.* (2018), O. Pylypovych & Kh. Ternovetska (2023). Human activity has a significant impact on water systems (pollution, water flow regulation, urbanisation). Hydroecological assessments are often limited to local impacts or specific parameters, but do not always take into account the complex and long-term effects of anthropogenic pressures that may affect river or water systems at a broader regional or global level.

An important method of studying river systems is the method of comparing topographic maps of different

times. Comparing large-scale maps of the same scale allows to track how human activities have affected the river network, such as infrastructure construction, marsh drainage, land reclamation, or urbanisation. Changes in river channels are often the result of impacts on the hydrological regime (creation of reservoirs, changes in the runoff system, changes in vegetation, etc.). For example, a detailed analysis of changes not only in the hydrological network, but also in the development of dangerous exogenous processes in the Blahnit River Valley, Romania, was carried out by comparing large-scale maps by C. Răducă *et al.* (2021). This method of research is possible for a limited time period, because accurate topographic maps of the 1:25,000 scale are available only from the first half of the 20th century. Austrian topographic maps of the 18th century were used by K. Witkowski & M. Witkowski (2018) to study the impact of water mills on the hydrological network of the Polish city of Wadowice and other areas within the Carpathian Region of the Lesser Poland Voivodeship. According to scientists, the functioning of mills is an important factor that led to the transformation of the river network.

It is advisable to use multi-scale maps to analyse changes in the hydrological network over a longer period of time. For the city of Lviv, this methodology was applied by G. Bayrak (2016), and described in detail the changes in the river network over a period of more than 200 years, but her research was limited to the year 2000 and did not include all the rivers in the northern outskirts of Lviv. That is why a detailed analysis of changes in the river network of the northern outskirts of Lviv was carried out using topographic maps of a scale range from 1:25,000 to 1:100,000. Studying old topographic maps allowed to understand what river systems and surrounding areas were like in the past. This is especially important for the development of projects to restore rivers and natural ecosystems, as the initial state can be determined and compared with the changes that have occurred over time. Historical data obtained by comparing topographic maps can be used to model future changes in river systems. This is useful for predicting the impact of climate change, urbanisation, or other factors on river systems. Therefore, comparing topographic maps of different time periods is a valuable method for multidimensional analysis of river systems, providing information about their evolution, the impact of human activities, environmental changes, and planning for future water management.

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Conclusions

Based on the analysis of anthropogenic transformation of the water network of the northern part of Lviv, the authors concluded that within the northern part of Lviv there was a decrease in the length of open channels, as well as the water content of all watercourses. This is due to both natural (changing climatic conditions) and anthropogenic (excessive development, destruction of slopes, creation of new highways, etc.) factors. Since the second half of the 18th century, the length of the natural channel of the Holoskivskyy stream has decreased by 3.8 km, the Zboivskyy stream by 2.0 km, and the Malekhivskyy stream by 2.6 km. A decrease in ponds and watermills was recorded. The largest number of ponds (15 units; 10.3 hectares) on streams was found in the second half of the 18th century. In the future, the number and area of ponds decreased. The lowest figures fall on the interwar Polish period, when only four ponds with a total area of 2.5 hectares were recorded. During the Soviet period, the number and area of ponds increased (9 units totalling 4.6 hectares) and reached the level that existed in the second half of the 19th century. There are two ponds left in the area of the open stream of Holoskivskyy stream, the largest of which is Stosyk Pond (0.9 hectares). As for the water mills, they were located on ponds in villages: Holosko Velyke, Zamarstyniv, Zboyishcha, and Malekhiv, there were 14 water mills. After that, the number of mills steadily decreased: at the beginning of the 19th century – nine; in the second half of the 19th century – seven; in the interwar period – five. After the World War II, the operation of all water mills was stopped. A significant decrease in the water content of streams, which is due to the intensive transformation and development of urban space, led to their sewerage. The best water availability situation is observed in the upper part of the Holoskivskyy stream, where many springs have been preserved, while in the upper parts of the Zboivskyy and Malekhivskyy streams, most springs have dried up. The prospect of further research is to measure the water content of watercourses with open channels, create a GIS model of their catchments, identify coastal protection strips and sanitary zones of the springs feeding these watercourses in order to implement environmental protection measures to preserve them.

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Conflict of Interest

None.

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Аналіз антропогенної трансформації гідрографічної мережі в північній частині Львова на основі картографічних джерел

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✔ **Анотація.** Поява нових та ущільнення існуючих міських просторів у Львові призводить до антропогенної трансформації гідрографічної мережі. Метою дослідження був аналіз ступеня перетворення водних об'єктів у північній частині міста на основі картографічних джерел. Дослідження охоплювало північну частину Львова, смт. Дубляни, села: Малехів, Великі Грибовичі, Збиранка і Муроване. Вивчення водних об'єктів проведено за допомогою топографічних карт масштабного ряду від 1:25 000 до 1:100 000, що дали змогу охопити часовий період у понад 240 років. Відзначено чіткі тенденції до зменшення довжини відкритих русел, кількості приток і водності Голосківського, Збоївського і Малехівського потоків, що зумовлено природними та антропогенними чинниками. Довжина природного русла Голосківського потоку зменшилася з 4,7 до 0,9 км, Збоївського потоку – з 5,2 до 3,2 км, а Малехівського потоку – з 7,9 до 5,3 км. Найбільше ставів (15 одиниць; 10,3 га) на потоках зафіксовано в другій половині XVIII ст. У подальшому спостерігалось зменшення як кількості, так і площ ставів. Найнижчі показники припадають на міжвоєнний польський період, коли обліковано лише 4 стави загальною площею 2,5 га. У радянський період кількість і площа ставів дещо зросла (9 одиниць; 4,6 га) та досягла рівня, що існував у другій половині XIX ст. На ставах у селах Голоско Велике, Замарстинів, Збоїща і Малехів діяло 14 водяних млинів. Відтоді чисельність млинів зменшувалася: на початку XIX ст. – 9; у другій половині XIX ст. – 7; у міжвоєнний період – 5. Після Другої світової війни функціонування водяних млинів припинено. Проведений аналіз ступені трансформації гідрографічної мережі спрямований на корекцію плану розвитку північної частини міста та впровадження системи екологічного менеджменту

✔ **Ключові слова:** потік; русло; став; млин; топографічна карта



Long-term consequences of the Chornobyl disaster for aquatic ecosystems: A retrospective analysis and prognosis

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✓ **Abstract.** Radioactive contamination of aquatic ecosystems as a result of anthropogenic disasters poses a serious threat to the environment and human health. The purpose of the study was to comprehensively analyse the long-term consequences of the Chornobyl disaster for aquatic ecosystems. The methodology included retrospective data analysis, field research, laboratory experiments, and mathematical modelling. The retrospective analysis covered historical data from 1986; field studies included sampling of water, sediments, and biota; laboratory experiments focused on studying the effects of radiation on aquatic organisms; mathematical modelling allowed predicting long-term trends. Changes in aquatic biocoenoses for the period 1986-2024 were analysed. The dynamics of concentrations of basic radionuclides ^{137}Cs , ^{90}Sr , and ^{241}Am in components of aquatic ecosystems, migration processes of radionuclides in the aquatic environment, and their bioaccumulation in organisms of various trophic levels was investigated. Special attention was paid to the impact of chronic radiation pollution on biodiversity, productivity, and genetic structure of aquatic populations. Changes in the species composition and number of key groups of hydrobionts were analysed. Based on long-term data and modern models, forecasts have been developed for the further development of the radioecological situation in the aquatic ecosystems of the exclusion zone until 2070-2090. A set of innovative measures to minimise negative consequences was proposed, including the use of nanotechnologies, genetically modified organisms, and automated monitoring systems. The need for international cooperation and the creation of a global database for long-term management of polluted aquatic ecosystems was substantiated. The results of the study are important for developing strategies for environmental management of radioactively contaminated areas and preparedness for possible future radiation incidents

✓ **Keywords:** nuclear accident; hydrobionts; radioactive isotopes; accumulation; environmental impact; radiation ecology

✓ Introduction

The Chornobyl disaster, which occurred on April 26, 1986, remains one of the largest anthropogenic accidents in the history of mankind, the consequences of which continue to affect the environment even decades later. Aquatic ecosystems, which play a key role in the migration and redistribution of radionuclides in the natural environment, are particularly vulnerable to radiation pollution. Reviews of the consequences of the Chornobyl accident note the importance of long-term monitoring and research of the environmental consequences of radiation pollution, which requires constant attention of scientists. The importance of long-term research for understanding the environmental

consequences of radiation pollution was emphasised by N.A. Beresford *et al.* (2020), who noted that radionuclide contamination of water bodies remains a key problem in the Chornobyl Exclusion Zone. The long-term effects of chronic exposure on the genetic structure of aquatic populations attract special attention from researchers. O.Ye. Kaglyan *et al.* (2019) found that the processes of bioaccumulation of radionuclides, in particular ^{137}Cs (Caesium-137) and ^{90}Sr (Strontium-90), depend on the trophic level and ecological group of fish, with the highest rates in predatory species. These changes can have far-reaching implications for the long-term sustainability and adaptability of aquatic ecosystems.

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The uneven radionuclide contamination of water bodies highlights the need for a differentiated approach to assessing radioecological risks. E.V. Kashparova *et al.* (2020) revealed significant differences in the content of ^{137}Cs in fish from different reservoirs of the exclusion zone, which indicates the complexity of migration processes and accumulation of radionuclides. These data are important for understanding the dynamics of pollution and developing effective water management strategies in the exclusion zone. The accumulation of long-lived transuranic elements in bottom sediments requires special attention. Research by V.O. Kashparov *et al.* (2020) showed the dynamics of the behaviour of radioactive particles from Chernobyl in the environment. This highlights the importance of developing effective methods for the rehabilitation of contaminated water bodies that can significantly reduce the level of radiation load on aquatic ecosystems.

H. Sato *et al.* (2023) investigated changes in radionuclide concentrations and ground water levels before and after lowering the water level in the cooling pond of the Chernobyl Nuclear Power Plant (NPP). Their study highlighted the importance of understanding hydrological processes in the context of radionuclide migration and their impact on aquatic ecosystems. A.Ye. Kaglyan *et al.* (2021) investigated the dynamics of specific activity of ^{90}Sr and ^{137}Cs in representatives of the ichthyofauna of the Chernobyl Exclusion Zone. Their research has shown that fish pollution levels remain high, especially in closed water bodies, highlighting the need to continue monitoring and develop measures to minimise radiation exposure to aquatic organisms. A. Konoplev *et al.* (2020) examined the mobility and bioavailability of Chernobyl-derived radionuclides in the soil-water system. Their study demonstrated the complexity of radionuclide migration processes in the aquatic environment and the importance of understanding these processes for predicting the long-term effects of pollution.

The issue of developing effective methods of rehabilitation of polluted water bodies remains relevant. This study will be important for understanding the long-term environmental impacts of nuclear accidents and developing effective strategies for managing contaminated areas. The purpose of this study was to comprehensively analyse the long-term consequences of the Chernobyl disaster for aquatic ecosystems, including a retrospective analysis of changes from 1986 to 2024 and the development of forecasts for the further development of the situation. The objectives of the study were: analysis of the dynamics of radionuclide pollution of water bodies for the period 1986-2024; assessment of the influence of the radiation factor on biodiversity and productivity of aquatic ecosystems; investigation of the processes of bioaccumulation of radionuclides in aquatic organisms; forecasting of the further development of the situation in the aquatic ecosystems of the Chernobyl zone; development of recommendations on measures to minimise the negative consequences of radiation pollution of aquatic ecosystems.

✓ Materials and Methods

The study of the long-term consequences of the Chernobyl disaster for aquatic ecosystems was conducted between the beginning of 2023 and June 2024 and included several stages. Data from radioecological monitoring of water bodies of the Chernobyl Exclusion Zone for the period 1986-2024 were used for collection and retrospective analysis. The sources of information were: reports of international scientific expeditions International Atomic Energy Agency (2020), United Nations Scientific Committee on the Effects of Atomic Radiation (2022), archival materials of the State Agency of Ukraine on Exclusion Zone Management (2023); databases of the Institute of Hydrobiology, National Academy of Sciences of Ukraine (2024); publications in peer-reviewed scientific journals, in particular "Journal of Environmental Radioactivity" (Elsevier), "Science of The Total Environment" (Elsevier).

During 2023-2024, 3 expeditions were conducted to the Chernobyl Exclusion Zone including 8 expeditions to contaminated and adjacent contaminated areas. 11 water bodies of various types were studied: rivers (Prypiat, Uzh), lakes (Glyboke, Daleke), reservoirs (Kyiv Reservoir), cooling ponds of the Chernobyl NPP. Samples of water (surface layer and bottom layer), bottom sediments (0-5 cm and 5-10 cm), aquatic plants (submerged, floating, and airborne) and fish of various ecological groups were taken in each water body. The content of radionuclides ^{137}Cs , ^{90}Sr , ^{241}Am (Americium-241) in the selected samples was determined by gamma spectrometry and radiochemical analysis. The following equipment was used: ORTEC GEM-C5060P4-B gamma-ray spectrometer (ORTEC, USA) with an ultrapure germanium detector; QUANTULUS-1220 beta spectrometer (PerkinElmer, USA); ORTEC OCTETE PC alpha spectrometer (ORTEC, USA). The equation was used to calculate the specific activity of radionuclides:

$$A = \frac{(N - N_F)}{(\varepsilon \times m \times t)}, \quad (1)$$

where A – specific activity of radionuclide, Bq/kg; N – count rate at the peak of full absorption; N_F – background count rate; ε – registration efficiency; m – sample weight, kg; t – measurement time, s. To assess the effect of the radiation factor on aquatic organisms, an analysis of species diversity was performed using the Shannon and Simpson indices. The Shannon index was calculated using the equation:

$$H' = -\sum(pi \times \ln \times pi), \quad (2)$$

where pi – proportion of individuals of the i -th species. Cytogenetic studies of fish and amphibians (micronucleus test). The micronucleus frequency (MNF) was calculated using the equation:

$$MNF = \frac{\text{number of cells with micronuclei}}{\text{total number of cells analysed}} \times 100\%. \quad (3)$$

Assessment of the reproductive potential of key species included an analysis of the fecundity and survival of offspring. Mathematical models were developed using ECOLEGO 6 software suite (Facilia AB, Sweden) to predict the long-term dynamics of radionuclide contamination of aquatic ecosystems. The model considered the following processes: physical decay of radionuclides; migration of radionuclides between ecosystem components; hydrological regime of water bodies; biological processes of accumulation and excretion of radionuclides. The basic equation of the model had the form:

$$dC/dt = -\lambda C + I - O, \tag{4}$$

where C – radionuclide concentration; λ – radioactive decay constant; I – radionuclide intake rate; O – radionuclide removal rate. Statistical data processing was performed using the STATISTICA 12.0 software suite. Methods of descriptive statistics, correlation and regression analysis were applied. The Student t-test and ANOVA were used to assess the validity of differences. To assess the radioecological state of aquatic ecosystems, the following criteria were used: permissible levels of radionuclides in drinking water in accordance with the standards of radiation safety of Ukraine (Ministry of Health of Ukraine, 1997); reference levels of irradiation of aquatic organisms in accordance with the recommendations of the International Commission on Radiological Protection (2008); radioecological risk indices calculated using the ERICA tool.

The research was coordinated and conducted in compliance with the following radiation safety and bioethics requirements: European Convention for the Protection of Vertebrate Animals Used for Experimental and Other Scientific Purposes (1986); Convention on Biological Diversity (1992); Law of Ukraine No. 39/95-BP (1995); basic sanitary rules for ensuring radiation safety of Ukraine (State Nuclear Regulatory Committee of Ukraine, 2005); Law of Ukraine No. 3447-IV (2006); recommendations of the International Commission on Radiological Protection (2007); Code of Ethics of the Scientist of Ukraine (National Academy of Sciences of Ukraine, 2010). All procedures with animals were approved by the bioethics committee of the Institute of Hydrobiology of the National Academy of Sciences of Ukraine (Protocol No. 2023-05 of 15.03.2023). Application

of an integrated approach that included retrospective analysis, field research, laboratory experiments, and mathematical modelling helped to comprehensively assess the long-term consequences of the Chornobyl disaster for aquatic ecosystems and formulate scientifically based forecasts of their further development.

✓ Results and Discussion

Dynamics of radionuclide contamination. Analysis of long-term monitoring data shows that the main dose-forming radionuclides in the aquatic ecosystems of the Chornobyl zone remain ^{137}Cs and ^{90}Sr . Their concentration in the water is gradually decreasing, but still exceeds pre-accident indicators. According to research, the concentration of ^{137}Cs in the water of reservoirs of the exclusion zone for the period 1986-2024 decreased by an average of 100-1,000 times, and ^{90}Sr – 10-100 times. However, these indicators still exceed the permissible levels of radionuclides in drinking water. Long-lived radionuclides accumulate in bottom sediments, in particular ^{241}Am , which may become a source of secondary water pollution in the future. Research has shown that the concentration of ^{241}Am in the bottom sediments of some reservoirs of the exclusion zone has increased 2-3 times over the past 20 years due to the collapse ^{241}Pu (Plutonium-241). An important aspect is the uneven radionuclide contamination of water bodies. The highest levels of pollution are observed in closed reservoirs and river backwaters, where radionuclides accumulate. Instead, in flowing bodies of water, such as the Prypiat River, more intensive self-purification of water is observed.

An important aspect is the investigation of radionuclide accumulation in the food chains of aquatic ecosystems. Studies have shown that accumulation coefficients of ^{137}Cs and ^{90}Sr in hydrobionts of different trophic levels can differ tenfold. This creates potential risks for higher trophic levels, including birds and mammals that feed on fish. Such data highlight the need for long-term monitoring and management of radioecological risks in the aquatic ecosystems of the Chornobyl Exclusion Zone and in the contaminated territories adjacent to the exclusion zone in Zhytomyr and Kyiv regions. Long-term monitoring has shown that the concentration of the main dose-forming radionuclides (^{137}Cs and ^{90}Sr) in water gradually decreases, but still exceeds pre-accident indicators (Fig. 1).

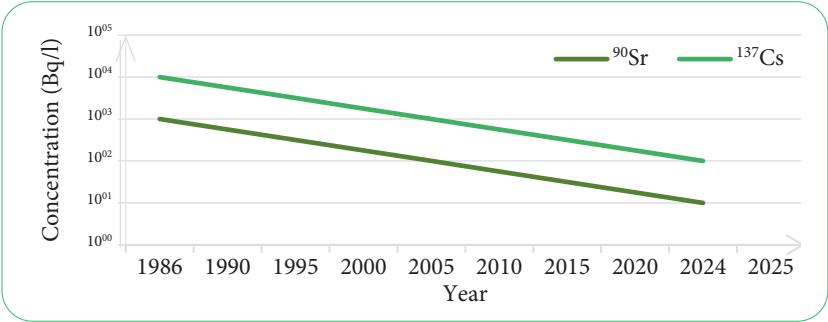


Figure 1. Concentration dynamics of ^{137}Cs and ^{90}Sr in water bodies, 1986-2024
Source: compiled by the author

As can be seen from the graph, the concentration of both radionuclides significantly decreased during the study period. In the first years after the accident, concentration of ¹³⁷Cs was higher than ⁹⁰Sr, which is explained by the difference in the physicochemical properties of these elements and the features of their release during an accident. Over time, there was a more intense decrease in concentration of ¹³⁷Cs compared to ⁹⁰Sr. This is conditioned by the fact that ¹³⁷Cs has a greater sorption capacity by bottom sediments and soil, whereas ⁹⁰Sr remains more mobile in the aquatic environment. For the period 1986-2024, concentration of ¹³⁷Cs in water decreased by an average of 100-1,000 times, and ⁹⁰Sr – 10-100 times. These results are consistent with the data obtained by A.Ye. Kaglyan *et al.* (2021), who also noted a similar trend. However, it is important to note that the rate of decrease in the concentration of radionuclides in different types of water bodies differs. In closed reservoirs, the self-cleaning process is slower than in flowing ones. As of 2024, the concentration of both radionuclides has decreased by 2-3 orders of magnitude compared to 1986, but still exceeds pre-accident levels. This trend highlights the need for

further monitoring of the processes of self-purification of aquatic ecosystems.

Bioaccumulation of radionuclides. The processes of bioaccumulation of radionuclides in aquatic organisms remain an urgent problem. Studies show that accumulation rates ¹³⁷Cs and ⁹⁰Sr in fish depends on their trophic level and ecological group. The highest rates were observed in predatory fish species that are at the top of the food chain. Accumulation coefficients of ¹³⁷Cs in the muscle tissue of predatory fish (pike, catfish, perch) can reach 104-105, while in non-predatory fish (crucian carp, roach, bream) are usually an order of magnitude lower. For ⁹⁰Sr, the highest accumulation rates were observed in fish bone tissue, reaching values of 103-104. An expanded set of hydrobiont species allows identifying the importance of species-specific features in bioaccumulation processes. Each species has its own unique characteristics of radionuclide accumulation, which depend not only on the trophic level, but also on the features of physiology and ecology. The study of bioaccumulation processes of radionuclides in aquatic organisms has shown that the accumulation coefficients of ¹³⁷Cs and ⁹⁰Sr in fish depends on their trophic level and ecological group (Table 1).

Table 1. Radionuclide accumulation rates in different fish species

Type of fish	Accumulation rate of ¹³⁷ Cs	Accumulation rate of ⁹⁰ Sr
Pike	9,800 ± 950	380 ± 40
Catfish	8,200 ± 800	350 ± 35
Perch	7,500 ± 720	420 ± 45
Crucian carp	3,100 ± 300	580 ± 60
Roach	2,300 ± 210	510 ± 55
Bream	1,900 ± 180	490 ± 50

Note: average values ± standard error is given (*n* = 30 for each type)
Source: compiled by the author

The results of the study showed that predatory fish species (pike, catfish, perch) have higher accumulation rates of ¹³⁷Cs compared to non-predatory species (roach, bream). This is conditioned by biomagnification processes – an increase in the concentration of pollutants at higher trophic levels of the food chain. And this pattern is consistent with the data obtained by O.Ye. Kaglyan *et al.* (2019), who also noted higher levels of radiocesium accumulation in predatory fish. For ⁹⁰Sr, the difference between predatory and non-predatory species is less pronounced, which is conditioned by the features of accumulation of this radionuclide mainly in the bone tissue of fish. High accumulation rates (up to 105 for ¹³⁷Cs) indicate a significant potential for bioaccumulation of radionuclides in fish, which creates potential risks to human health when consuming fish products from polluted reservoirs. It is important to note that bioaccumulation processes are seasonal in nature. Studies have shown that the concentration of radionuclides in fish tissues is usually higher in the summer, which is associated with the intensification of metabolic processes and changes in the feed base. Special attention should be paid to the accumulation of radionuclides in aquatic plants, which play

an important role in the migration and redistribution of radioactive elements in aquatic ecosystems. According to the data obtained, some species of aquatic macrophages (cattails, reeds) can accumulate ¹³⁷Cs and ⁹⁰Sr in concentrations 103-104 times higher than their content in water. The scheme of Figure 2 shows the main migration routes of radionuclides in the aquatic ecosystem of the Chornobyl Exclusion Zone.

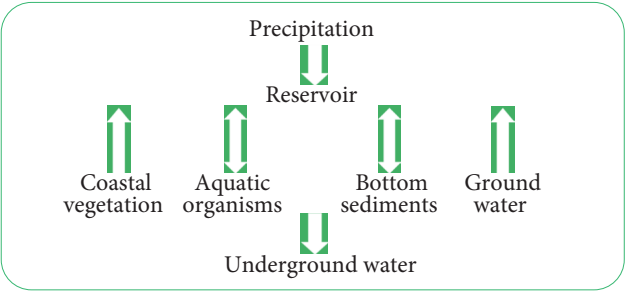


Figure 2. Radionuclide migration routes in the aquatic ecosystem

Source: compiled by the author

The diagram demonstrates the complexity and interrelation of radionuclide migration processes in the aquatic environment. Precipitation is one of the sources of radionuclides entering the reservoir, especially in the first years after the accident. In the reservoir itself, there is a complex process of redistribution of radionuclides between water, bottom sediments, and aquatic organisms. Coastal vegetation plays an important role in bioaccumulation processes and can serve as a bioindicator of pollution. Bottom sediments are an important radionuclide depot and can become a source of secondary contamination during their remobilisation. Ground and groundwater are also involved in radionuclide migration, which highlights the need for a comprehensive approach to pollution monitoring.

Impact on biodiversity. Long-lived radionuclides accumulate in bottom sediments, in particular ^{241}Am , which may become a source of secondary water pollution in the future. Studies have shown that the concentration of ^{241}Am in the bottom sediments of some reservoirs of the exclusion zone has increased 2-3 times over the past 20 years due to the decay of ^{241}Pu . An important aspect is the uneven radionuclide contamination of water bodies. The highest levels of pollution are observed in closed reservoirs and river backwaters, where radionuclides accumulate. Instead, in flowing bodies of water, such as the Prypiat River, more intensive self-purification of water is observed. Considering the impact on biodiversity and productivity, the study shows that there have been significant changes in the structure of aquatic biocoenoses in the nearly 40 years since the accident. In the first years after the disaster, there was a sharp decline in the biodiversity and productivity of aquatic ecosystems. In particular, a significant decrease in the number and species diversity of phytoplankton, zooplankton and benthic organisms was recorded. It was found out that during the period 1986-2024, there was a gradual restoration of the species diversity of aquatic ecosystems (Fig. 3).

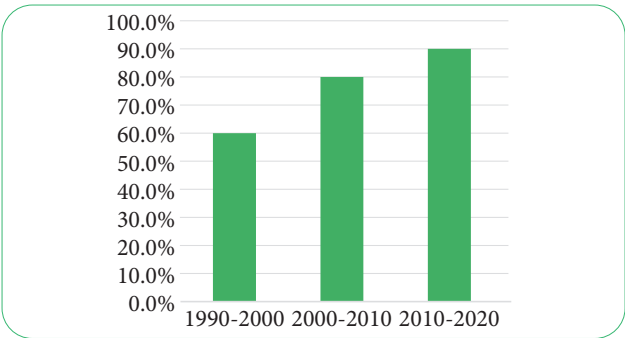


Figure 3. Dynamics of restoration of species diversity of aquatic ecosystems
Source: compiled by the author

The diagram shows the gradual restoration of the species diversity of aquatic ecosystems over time. In 1990, 4 years after the accident, species diversity was only about 40% of the pre-accident level. This was conditioned by acute radiation exposure and significant pollution of water bodies in the first years after the disaster. By 2000, there was a significant improvement in the situation – species diversity reached approximately 60% of the pre-accident level. This can be explained by the processes of self-purification of water bodies and the adaptation of organisms to new living conditions. In 2010, the indicator increased to 80%, and as of 2024, the species richness reached 90% of the pre-accident level. This trend indicates a high ability of aquatic ecosystems to recover, but also indicates that full recovery to a pre-accident state may take many more years or even decades. However, it is important to note that the structure of aquatic biocoenoses has undergone some changes. In particular, there is an increase in the number of some fish species, which may be due to the cessation of industrial fishing and a decrease in anthropogenic pressure. Radiation exposure has led to changes in the genetic structure of aquatic populations.

Studies have shown an increased mutation rate in fish and amphibians living in polluted water bodies. It is important to note that although quantitative indicators of species diversity are approaching pre-accident, the qualitative composition of communities may have undergone changes, which requires further study. Studies have revealed an increased frequency of cytogenetic disorders in aquatic organisms from the most polluted reservoirs. In particular, the frequency of micronuclei in peripheral blood red blood cells of fish from reservoirs with a high level of pollution was 2-3 times higher compared to control reservoirs ($p < 0.001$).

Forecasts and prospects. Based on the analysis and mathematical modelling, the authors of this study predict that the processes of self-purification of aquatic ecosystems will continue for several more decades. Estimated concentration of ^{137}Cs in the water of most reservoirs of the exclusion zone will reach pre-accident levels in about 50-70 years, that is, in 2070-2090. For ^{90}Sr , this period may be longer due to its higher mobility in the aquatic environment. Special attention should be paid to the accumulation of transuranic elements in bottom sediments. According to forecasts, the peak of accumulation of ^{241}Am in the bottom sediments of water bodies in the exclusion zone will be reached around 2050-2060, after which a slow decrease in its concentration will begin. These data correlate with predictions of V.O. Kashparov *et al.* (2020). The diagram (Fig. 4) provides a forecast of changes in concentration ^{241}Am in the bottom sediments of reservoirs of the Chornobyl Exclusion Zone for the period from 2024 to 2060.

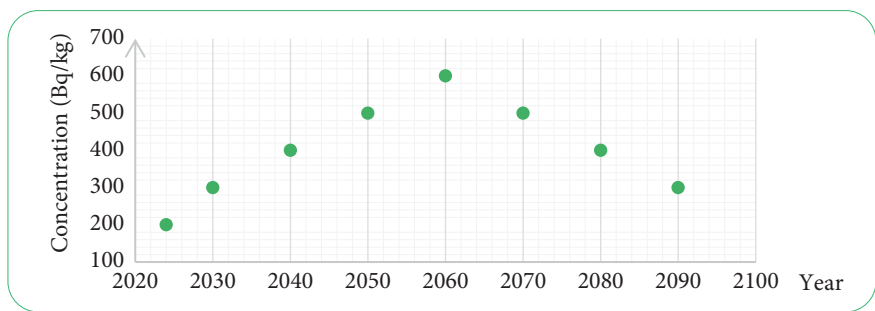


Figure 4. Concentration forecast of ^{241}Am in bottom sediments, 2024-2060

Source: developed by the author

The graph shows a gradual increase in concentration of ^{241}Am in bottom sediments until about 2050-2060, after which a slow decline is expected. This trend is explained by the fact that ^{241}Am is a decay product of ^{241}Pu , which has a half-life of 14.4 years. Increasing concentration of ^{241}Am is an important factor to consider when planning long-term management of contaminated areas. ^{241}Am has a long half-life (432 years) and may become a significant source of radiological exposure in the future. Projected decline in concentration after 2060 is conditioned by natural decay of ^{241}Am and the processes of its redistribution in the ecosystem. However, given the long half-life, ^{241}Am will remain an important factor in the radioecological situation in the exclusion zone for many centuries. It is expected that global climate changes may affect the hydrological regime of water bodies in the exclusion zone, potentially leading to changes in radionuclide migration. In particular, increasing the frequency of extreme weather events can increase the risk of secondary pollution due to erosion of contaminated soils and bottom sediments. An important aspect is predicting the long-term effects of chronic exposure on aquatic ecosystems. Studies show that even at low radiation doses, genetic changes in aquatic populations are possible, which can affect their adaptive abilities and the overall sustainability of ecosystems.

To minimise the negative consequences, it is necessary to continue long-term monitoring of aquatic ecosystems, develop and implement technologies for the rehabilitation of contaminated areas. Promising areas are phytoremediation using aquatic hyperaccumulator plants and bioremediation using specialised microorganisms. To minimise the negative consequences, in addition to the measures already mentioned, the following can be recommended: introduction of modern remote monitoring technologies (drones, satellite images) for more effective and safe monitoring of aquatic ecosystems of the exclusion zone; development and application of nanotechnological methods of water and bottom sediments purification from radionuclides, which can provide more effective extraction of pollutants;

creation of genetically modified microorganisms that can more effectively accumulate and/or transform radionuclides into less dangerous forms; development and implementation of automated early warning systems for changes in the radioecological situation in aquatic ecosystems; creation of an international centre for radioecological research at the Chornobyl Exclusion Zone for coordinating scientific efforts and sharing experience.

It is important to develop long-term (for 100-200 years) strategies for managing polluted areas, considering possible changes in ecosystems, climate change and the development of new technologies. It is necessary to integrate the acquired knowledge about the long-term effects of radiation pollution into training programmes in ecology, radiobiology, and environmental safety to train future specialists. It is recommended to create an international data bank for long-term monitoring of the radioecological situation in the aquatic ecosystems of the Chornobyl zone to ensure that scientists have access to this unique information. The proposed conclusions and recommendations highlight the complexity of the problem of long-term consequences of the Chornobyl disaster for aquatic ecosystems and the need to continue research and develop innovative approaches to the management of polluted areas. The experience gained in studying the impact of the Chornobyl disaster on aquatic ecosystems is crucial for developing strategies for managing radioactively contaminated areas and preparing for possible future radiation accidents. It is necessary to strengthen international cooperation in the field of radioecological research of aquatic ecosystems to exchange experience and develop effective methods for the rehabilitation of polluted reservoirs.

The results obtained on the long-term dynamics of radionuclide pollution of aquatic ecosystems of the Chornobyl zone are consistent with the conclusions of O.Ye. Kaglyan *et al.* (2019) on the gradual reduction of concentrations of ^{137}Cs and ^{90}Sr in water and hydrobionts, but confirm that pollution levels still exceed pre-accident rates. Their research has shown that accumulation rates ^{137}Cs and ^{90}Sr in

fish depends on their trophic level and ecological group, with the highest rates in predatory fish species. Similarly to the conducted observations, the restoration of the species diversity of aquatic ecosystems to 80-90% of the pre-accident level was revealed, but with changes in the structure of groupings. The author's predictions about the long-term behaviour of radionuclides in aquatic ecosystems consider the factors identified by V.O. Kashparov *et al.* (2020), in particular, the accumulation of transuranic elements in bottom sediments, which may become a source of secondary pollution in the future. Colleagues pointed to the problem of accumulation of long-lived transuranic elements, in particular ^{241}Am , in bottom sediments. Their research has shown that the concentration of ^{241}Am in some reservoirs of the exclusion zone has increased in recent years, which may become a source of secondary pollution in the future. The researchers also investigated the dynamics of the content of transuranic elements in soils and bottom sediments. Their results are important for understanding potential sources of secondary pollution of aquatic ecosystems in the future.

The Chornobyl disaster had a significant impact on aquatic ecosystems, which has continued to be studied for decades. N.A. Beresford *et al.* (2020) in their review highlighted the importance of long-term research to understand the environmental impacts of radiation pollution. Radionuclide contamination of water bodies remains a key problem in the Chornobyl Exclusion Zone. The researchers also developed a methodology for assessing the radiation impact on the wildlife of the Chornobyl zone, including aquatic ecosystems. Their approach helped to estimate the radiation doses of various animal and plant species, considering the specifics of their habitats. An important aspect of research related to the impact of the Chornobyl accident on aquatic ecosystems is the study of long-term changes in the composition and structure of freshwater megafauna. The study by F. He *et al.* (2019) showed a dramatic decline in the number of freshwater fish, amphibians, reptiles, and mammals that occupy the upper trophic levels globally. Similar trends may occur in radioactively contaminated water bodies in the Chornobyl zone, which requires a detailed study. Conservation of biodiversity, especially sensitive indicator species, should be a priority for the management of contaminated areas.

In addition, an important area of research is the study of the behaviour of radioactive particles formed as a result of nuclear accidents in aquatic ecosystems. Overview by G. Steinhäuser (2018) emphasised that such particles can be persistent and affect the migration of radionuclides in the environment for a long time. A detailed study of the appearance, propagation, and transformation of radioactive particles in the water systems of the Chornobyl zone can significantly contribute to the understanding of radionuclide migration processes. Complex models of radionuclide migration in aquatic ecosystems also play a key role in predicting the long-term behaviour of pollutants. The study by R. Bezhenar *et al.* (2023) was devoted to modelling the behaviour of ^{137}Cs and ^{90}Sr in the cooling pond of the Chornobyl

NPP before and after lowering the water level. Such models are necessary to develop effective strategies for managing polluted water bodies. An important aspect is the assessment of the impact of forest fires on the migration of radionuclides to the aquatic ecosystems of the Chornobyl zone. T. Fedoniuk *et al.* (2021) showed that significant fires in contaminated areas in 2020 led to secondary water pollution.

The problem of radioactive contamination of food products, in particular aquatic organisms, also remains relevant in the context of the Chornobyl accident. The study by N. Tanimura (2021) and S. Kong *et al.* (2022) on the situation in China and Japan after the Fukushima accident demonstrate the need for long-term monitoring of radioactivity in food products to protect public health. Similar measures should be applied in regions polluted by the Chornobyl disaster. T. Wada *et al.* (2019) demonstrated a significant difference in the accumulation of ^{137}Cs between marine and freshwater fish in the Fukushima accident area. These results point to the need for a differentiated approach to monitoring and managing radioactively contaminated water bodies of various types.

It is important to use international databases, such as the International plant names index (n.d.) and the IUCN Red List of threatened species (n.d.). These resources can help to identify rare and endangered species of hydrobionts that require special attention and protection in the face of radioactive contamination. A comprehensive approach to investigating the long-term effects of the Chornobyl accident on aquatic ecosystems, which combines retrospective analysis, field research, laboratory experiments, and mathematical modelling, reflects current trends in radioecological research. This approach helps to comprehensively assess the dynamics of processes occurring in polluted water bodies and predict their further development.

The results of this study, combined with other similar research, provide important information for developing effective strategies for managing radioactively contaminated aquatic ecosystems and preparing for possible future accidents. The study demonstrates the versatility of the problem of the long-term consequences of the Chornobyl disaster for aquatic ecosystems and highlights the need for further comprehensive research in this area. The results of studies of aquatic ecosystems of the Chornobyl Exclusion Zone emphasise the importance of an integrated approach to assessing the environmental consequences of anthropogenic disasters and the need for long-term planning of environmental protection measures.

✓ Conclusions

The long-term impact of the Chornobyl disaster on aquatic ecosystems remains significant even almost 40 years after the accident. Radionuclide contamination of water bodies, although reduced, still exceeds pre-accident levels, especially in closed reservoirs and bottom sediments. There is a gradual decrease in the concentration of the main dose-forming radionuclides (^{137}Cs and ^{90}Sr) in water, but their accumulation in bottom sediments creates a risk

of secondary contamination. Special attention is drawn to the increase in concentration of ^{241}Am , which may become a significant factor of radiological influence in the future. There is a gradual restoration of the biodiversity of aquatic ecosystems, although with certain differences from the pre-accident state. Species diversity has reached 80-90% of the pre-accident level, but there are changes in the structure of species dominance and their ratio. The processes of bioaccumulation of radionuclides in aquatic organisms remain an urgent problem, especially for species at the top of the food chain. Accumulation coefficients of ^{137}Cs in predatory fish pose potential risks to human health when consuming fish products from polluted water bodies.

Chronic radiation exposure has led to genetic changes in aquatic populations that can affect their adaptive abilities and the resilience of ecosystems as a whole. These effects require further study to understand the long-term effects of radiation exposure on ecosystems. Forecasts indicate that the processes of self-purification of aquatic ecosystems will continue for several more decades. It is expected

that the concentration ^{137}Cs in the water of most reservoirs of the exclusion zone will reach pre-accident levels around 2070-2090, while for ^{90}Sr this period may be longer. It is predicted that by 2050 the concentration of ^{241}Am in bottom sediments will reach its peak, after which a slow decline will begin. In the long term (100-200 years), a gradual stabilisation of the radioecological situation in aquatic ecosystems can be expected, but with the establishment of new ecological equilibria that differ from pre-accident ones. Further research should focus on studying long-term genetic and epigenetic changes in aquatic organisms, developing innovative bioremediation methods, and creating comprehensive models for predicting the radioecological situation in climate change.

✓ Acknowledgements

None.

✓ Conflict of Interest

None.

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Довгострокові наслідки Чорнобильської катастрофи для водних екосистем: ретроспективний аналіз та прогнози

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✔ **Анотація.** Радіоактивне забруднення водних екосистем внаслідок техногенних катастроф становить серйозну загрозу для навколишнього середовища та здоров'я людини. Мета дослідження полягала в проведенні комплексного аналізу довгострокових наслідків Чорнобильської катастрофи для водних екосистем. Методологія включала ретроспективний аналіз даних, польові дослідження, лабораторні експерименти та математичне моделювання. Ретроспективний аналіз охопив історичні дані з 1986 року; польові дослідження включали відбір проб води, донних відкладень та біоти; лабораторні експерименти зосередилися на вивченні впливу радіації на водні організми; а математичне моделювання дозволило спрогнозувати довгострокові тенденції. Проаналізовано зміни у водних біоценозах за період 1986-2024 років. Досліджено динаміку концентрацій основних радіонуклідів ^{137}Cs , ^{90}Sr та ^{241}Am у компонентах водних екосистем, процеси міграції радіонуклідів у водному середовищі та їх біоаккумуляції в організмах різних трофічних рівнів. Особлива увага приділена впливу хронічного радіаційного забруднення на біорізноманіття, продуктивність та генетичну структуру популяцій водних організмів. Проаналізовано зміни у видовому складі та чисельності ключових груп гідробіонтів. На основі багаторічних даних та сучасних моделей розроблено прогнози щодо подальшого розвитку радіоекологічної ситуації у водних екосистемах зони відчуження до 2070-2090 років. Запропоновано комплекс інноваційних заходів із мінімізації негативних наслідків, включаючи застосування нанотехнологій, генетично модифікованих організмів та автоматизованих систем моніторингу. Обґрунтовано необхідність міжнародної співпраці та створення глобальної бази даних для довгострокового управління забрудненими водними екосистемами. Результати дослідження мають важливе значення для розробки стратегій екологічного менеджменту радіоактивно забруднених територій та готовності до можливих майбутніх радіаційних інцидентів

✔ **Ключові слова:** ядерна аварія; гідробіонти; радіоактивні ізотопи; накопичення; екологічний вплив; радіаційна екологія



Environmental consequences of oil and gas extraction on the example of the Bytkiv-Babchenskyi Oil and Gas Field

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✓ **Abstract.** Most technological processes create an anthropogenic burden on the environment, and the oil and gas industry is no exception. Due to oil and gas production in the Bytkiv-Babchenskyi Field area, there is gas pollution in the territory of Pasichna and Bytkiv settlements, oil leaks to the surface, however, it is necessary to strive to minimise the negative impact and preserve the environment. The purpose of the study was to conduct a comprehensive analysis of the ecological state of the atmosphere, soils, hydrosphere and technogenic physical fields (radiation, noise, vibration, electromagnetic) near various oil and gas production facilities of the Bytkiv-Babchenskyi Field to determine the man-made impact of the oil and gas production process. The following methods were used: observation, measurement of environmental indicators, meteorological and physical field parameters, and laboratory analysis methods. A wide range of modern instruments was used, which allows for rapid analysis and determination of physical field parameters. In the laboratory, a more detailed analysis of water and soil samples was carried out using physico-chemical methods of analysis.

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The determined chemical, physico-chemical indicators of water quality, the content of volatile organic compounds and polyaromatic hydrocarbons complied with the regulatory standards. Among the toxic elements, strontium was detected, the content of which did not exceed the maximum permissible concentration. In terms of salt content, the hydrocarbonate water is slightly mineralised. The soils are low-saline with a neutral pH of the soil solution. The content of mobile iron, phosphorus, and nitrogen compounds is very low, low, and medium, respectively, and organic matter is very high. It was established that the parameters of anthropogenic physical fields do not exceed the permissible standards. The results of the study showed that the technogenic impact of the oil and gas production process on the air, water bodies and soils is within the permissible limits. The practical significance of the results obtained is the comprehensive monitoring of the state of natural objects throughout the year, which is important for oil and gas industry professionals when assessing the environmental impact of oil and gas production facilities and developing environmental protection measures

✔ **Keywords:** oil and gas industry; man-made physical fields; physical and chemical research; gas pollution; atmospheric air; soils; hydrosphere objects

✔ Introduction

Oil and gas companies are among the main polluters of the environment. This is due to the hydrocarbon production process itself, as well as to their primary preparation, transportation and processing. Pollution occurs both during the technological process and in the event of emergency situations. Emergencies are the most dangerous, as a large area of land is contaminated in a relatively short amount of time, which loses its ability to recover for a long period of time. The main causes of emergencies are salvo emissions, fires and damage to pipelines. The main sources of environmental pollution at oil and gas production facilities are production and injection wells, reservoir pressure maintenance pumping stations, group installations, individual well assemblies and other industrial oil and gas production facilities, which are characterised by their density across the entire oil and gas field. Environmental problems are caused by a number of factors – natural, technological and even historical – which cannot be separated from each other and which, to some extent, are interrelated and have mutual cause and effect. Therefore, the emergence and development of environmental problems begins with the first attempts to extract oil and gas.

As noted by J. Lubas (2021), oil and gas production in the Carpathian Region began at the end of the eighteenth century and was uncontrolled, and 1853, according to O. Gvozdevich (2021), is the year of foundation of the Galician oil industry. The problem of old oilfields is primarily related to abandoned wells, which, for example, according to J.P. Williams *et al.* (2020), number several million in the United States and up to 400,000 in Canada, and are a source of constant hydrocarbon gas emissions. T.M. Yatsyshyn *et al.* (2022) found that there are also abandoned wells of the old stock in the Carpathian Region, and environmental pollution is associated with methane emissions, which is also a greenhouse gas. In addition, data on the location of a significant number of wells drilled during the Austro-Hungarian Empire and Poland from the nineteenth century to 1939 has been lost in most cases. Therefore, the presence of old oil and gas wells in the study area can be considered the first cause of man-made environmental impacts.

The emergence of environmental problems is caused by the peculiarities of the geological structure of the Carpathian Region, the complexity of which is noted in the research of S. Wolkowicz *et al.* (2020). The presence of a significant number of tectonic faults causes the emanation of hydrocarbon gases, oil and formation water leaks to the surface under the influence of reservoir pressure. This is the reason for the natural pollution of the Bytkiv-Babchenskyi Oil and Gas Field. However, the tectonic processes that are intensively occurring in the Carpathian Region can also cause a violation of the wellbore integrity. This issue is especially relevant for the old well stock, where the leakage of old casing may occur due to the cementing technology used at the time. L. Bilous (2021) studied the historiography of environmental problems that arise at oil and gas production facilities on the example of the Boryslavnaftogaz Oil and Gas Production Division. It is noted that many scientists have studied the complex negative impact of the development and operation of the Boryslav oil field on all ecological systems and their components – atmospheric air, soil, water and biological resources. On the other hand, the territory of the Bytkiv-Babchenskyi Field is characterised by a fairly dense location of all oil and gas production facilities. For example, there are only about 600 wells in the field, more than 70% of which are not in operation for various reasons.

The Bytkiv-Babchenskyi Oil and Gas Field is located in the Nadvirna oil and gas production area of the Carpathian Region, which is one of the oldest oil fields not only in the Carpathian Region but also in Europe. The region is characterised by complex geological and tectonic conditions, and oil and gas production leads to intensification of fracture formation in rocks and increased migration of hydrocarbons from the subsoil. The territory of the Bytkiv-Babchenskyi Field is a densely populated area of Ivano-Frankivsk Region with a population of over 20,000 people. There are also six nature reserve sites, and some species of animals are protected under the Convention on the Conservation of Wild Flora and Fauna and Natural Habitats in Europe. The importance of conducting studies of the anthropogenic impact of oil and gas production facilities on environmental components is also related to the fact that

the Bytkiv-Babchenskyi Field is located in a densely populated area. The main settlements within its boundaries are Bytkiv, Markova, Maniava, Babche, Lukavets, Molodkiv, Sokolovytsia, Postoiata, Pasichna, Pniv, Bilozoryna. The Bytkiv-Babchenskyi Field has 6 objects of the nature reserve fund: Skit-Maniava forest reserve of national importance; Debrytsia protected tract; Syniachky protected tract; Hlybokyi protected tract of local importance; Komarnyky protected tract of local importance; Boiarske protected tract of local importance (The nature reserve fund..., 2023). Therefore, it seems important to determine the extent of the environmental impact of hydrocarbon production. The purpose of the study was to observe and assess changes in the quality indicators of the environment in the area of influence of oil and gas production facilities located in the Bytkiv-Babchenskyi Field.

✔ Literature Review

The history of the oil and gas industry in the Carpathian Region is an important historical aspect in shaping the current environmental problems of the oil and gas industry. Oil production in Galicia began in the mid-nineteenth century. In 1854, the Mining Statute was adopted, which allowed oil production by private individuals, as indicated in their research by V.S. Biletsky *et al.* (2019). However, the first well in Ivano-Frankivsk Region was drilled in Kolomyia district in 1872, and in Prykarpattia in 1861 in the Boryslav. The intensive production of hydrocarbons, primarily oil, is evidenced by the fact that in 1909, oil production in the Boryslav oilfield district accounted for 5% of global production. This significant development of the oil and gas industry necessitated the construction of pipelines. The first oil pipeline was built in 1886, and the first gas pipeline in 1912. As early as 1932, there were seven companies producing oil and gas in Galicia, transporting oil and gas raw materials through their own pipelines.

The Bytkiv-Babchenskyi Oil and Gas Field is located in the Podkarpatska oil and gas bearing region of the Nadvirna oil and gas production area, with an area of over 16,000 hectares, as noted by M. Vul (2003). Development of the field began in 1860. The field belongs to the Berehove section of the Carpathians and a group of folds in the central part of the Boryslavsko-Pokutska zone, and oil and gas condensate deposits are associated with the Deep Fold. The study of the geological and tectonic conditions of the field formation is important in terms of environmental issues, especially those of natural origin. The field area is located within the Nadvirna seismogenic zone, which is part of the Boryslavsko-Pokutska structural and facies zone of the Internal Zone of the Fore-Carpathian Trough, overlain by the thrust of the Skiba Zone of the Carpathians and where the Nadvirna moral and neotectonic node is located, as described in the collective monograph edited by M. Malovanyi (2020). The Bystrytsko-Nadvirna Fault is a deep tectonic fault, which is regional in nature and is located outside the study area. The fault is a zone of sub-parallel faults such as dip-slides, the amplitude of which in

the near-surface geological horizons ranges from the first metres to several tens of metres, while with depth it increases to 50-100 m and more. The fault zone is 100-200 m wide. V. Shlapynskyi (2018) pointed out that the geological structure of the territory is complex, with numerous structural faults. The horizontal displacement of identical folds can reach 10 km, and the amplitude of vertical displacement is 1.5-2 km.

The presence of tectonic faults causes emanation of hydrocarbons to the surface at all oil and gas fields in the world, especially in the territory of old oil fields with abandoned oil and gas wells. Since the study area is densely populated and oil and gas production facilities are located in the territory of settlements, assessing the level of air pollution in the areas where they are located is an important area of research into the environmental impact of oil and gas production. M.J. Munawar *et al.* (2022) emphasised that the main air pollutant is not only hydrocarbon gases, but also hydrogen sulphide. Not only natural gases, but also oil and produced water move through tectonic fractures under the influence of reservoir pressure. Therefore, in oil and gas production areas with complex geological and tectonic structure, oil and reservoir fluids leak to the surface. A significant number of such manifestations in Prykarpattia are associated with the Boryslav oil and gas condensate field, where the city of Boryslav is a man-made environmental disaster, as described in the research of many Prykarpattia scientists since the 70s of the last century. V. Filipovych *et al.* (2020) found that the area of methane pollution due to natural methane leakage in Boryslav is 20 km².

E. Ivanov *et al.* (2020), studying the problem of gas pollution in Boryslav and uncontrolled leakage of formation water, determined that natural pollution of the territory is superimposed on man-made pollution, which is associated with the improper arrangement of oil and gas production facilities. The consequences are the contamination of soil and hydrosphere. Therefore, it is necessary to take into account not only the quality composition of oil, but also the landscape of the territory, which will directly affect the degree of pollution of natural objects and the development of degradation processes. According to the research of M. Pavliuk *et al.* (2021), the oil of the Bytkiv-Babchenskyi Field is classified as light oil, as its density ranges from 750-800 kg/m³. The average light hydrocarbon content is 10-20%, and the aromatic group composition is aromatic. Oil may contain an increased sulphur content of 1-8%. The Bytkiv-Babchenskyi Field is subject to significant anthropogenic impact. There are also oil and gas discoveries in the study area, especially in the settlements of Bytkiv and Pasichna. Thus, the Bytkiv-Babchenskyi Oil and Gas Field is located in an area with a complex geological and tectonic structure with a widespread network of tectonic faults, which causes natural emanation of reservoir gases and oil to the surface. This results in natural gas pollution of the study area and the presence of soils contaminated with oil and formation water.

Materials and Methods

To determine the anthropogenic impact of the oil and gas production process on the territory of the Bytkiv-Babchenskyi Field, eight objects were selected, seven of which are wells and one group unit. The objects are located in different parts of the field, including in the territory of settlements, covering the maximum area of the Bytkiv-Babchenskyi Field. Because of the martial law in the country, it is impossible to provide a map of the study area with oil and gas production facilities. Since oil and gas production facilities are strategic objects of Ukraine, this article does not identify well numbers and group units. The observations were carried out in 2022-2023. To optimise the field studies, oil and gas facilities were divided into two groups: Group 1 is represented by facilities 1-4, Group 2 is represented by facilities 5-8, where the studies were conducted quarterly in 2022 and 2023, respectively. At each of the oil and gas production facilities, the state of environmental components – atmospheric air, water bodies and soils, and anthropogenic physical fields (noise, vibrating, radiative and electromagnetic) – was studied. Quarterly measurements made it possible to observe and assess changes in environmental quality indicators at the Bytkiv-Babchenskyi Field to determine the impact of oil and gas production facilities on the environment.

The atmospheric air studies were conducted in accordance with Article No. 29 of Law of Ukraine No. 2707-XII (1992) and Procedure for State Monitoring in the Field of Atmospheric Protection (2019). Observations were carried out in accordance with the requirements of the Generalised List of Maximum Permissible Concentrations (MPCs) and Tentatively Safe Exposure Levels (SELs) of Harmful Substances for the Water of Fishery Reservoirs (1991); Methodological Guidelines “Justification of Estimated Safe Exposure Levels (SELs) of Chemical Substances in the Atmospheric Air of Populated Areas” (2004); Hygienic Regulations No. 156/34439 (2020); and Hygienic Regulations No. 157/34440 (2020). The study was conducted in open areas that are well ventilated from all sides at a height of 1.5 m above the ground. When assessing the impact of oil and gas production on the air, the location of the study site was considered and the main meteorological factors such as temperature, relative humidity, wind speed and illumination were determined. The soil cover in the study area of the Bytkiv-Babchenskyi Field is homogeneous, and during the observation period (2022-2023), no accidents occurred, and no oil and formation fluids were recorded on the daylight surface from oil and gas production facilities. Therefore, a visual examination of soil samples and pH determination was carried out around each of the study sites. However, two sites were selected to control pollution, in the vicinity of oil and gas production facilities 2 and 3, from which soil samples were collected for physical and chemical analysis. Sampling and preparation for physical and chemical analysis was carried out in accordance with the regulatory documents (DSTU ISO 10381-1:2004, 2004; DSTU ISO 10381-2:2004, 2004; Environmental protection..., 2005).

According to DSTU 4287:2004 (2004), the maximum area of representativeness of a sampling point for a pollution examination in mountainous areas is 3 ha. The sampling points were selected to avoid the influence of extraneous factors that could affect the results and should not be sampled closer than 50 m from them. In this case, such factors included the roads of the settlement and forest belts. There were no areas of vegetation with a sharp difference from the background in the sampling area. At each of the two study sites of the Bytkiv-Babchenskyi Field, one combined soil sample was collected, consisting of a set of individual point samples combined in proportion to the area of the study site of 100×100 m around the oil and gas production facility. Soil sampling was carried out to determine the general quality of the soil, which does not require regular testing and can be carried out at certain (irregular) intervals. To assess the overall quality of the soil, the following factors were investigated: hydrogen ion exponent, hydrolytic acidity, mass fraction of organic matter, ammonia nitrogen, nitrate nitrogen, mobile phosphorus and iron compounds, exchangeable calcium, exchangeable magnesium, amount of absorbed bases, mass concentration of water-soluble sulphates. Since the study was conducted to determine the overall quality of the soil, soil samples were taken from a depth of 10-20 cm and are classified as spatial samples.

In 2022, water quality in the Bystrytsia Nadvirnianska River was monitored in the settlements of Bytkiv and Pasichna, as these settlements are heart to a significant number of oil and gas production facilities. Water samples were collected and analysed in accordance with the following regulatory documents: DSTU ISO 5667-6:2009 (2009); Procedure for Checking, Taking Water Samples and Conducting Their Analysis (2019); Environmental Quality Standards (ENSs) for Determining the Chemical State of a Surface Water Body (2019); and Hygienic Regulations No. 524/37860 (2022). In the Bystrytsia Nadvirnianska River in the settlements of Bytkiv and Pasichna, a simple water sample was taken, which is obtained by a single water intake for further chemical and physicochemical analysis. In addition, a 4-in-1 autonomous portable water laboratory AZ-8603 (AZ-Instrument, China) was used to perform proximal analyses of the following indicators at the sampling site: hydrogen ion exponent, salinity, dissolved oxygen, and temperature. The chemical and physicochemical indicators of water and soil pollution were determined in the water monitoring laboratory of the Western Region of the Dniester Basin Water Resources Administration, accredited in accordance with DSTU EN ISO/IEC 17025:2019 (2019). To study the impact of anthropogenic physical fields around 1-8 oil and gas production facilities of the Bytkiv-Babchenskyi Field, electromagnetic and radioactive radiation was measured to determine radionuclides, noise and vibrating characteristics during the technological blowing-out process of well and operation of the Pumpjack. Regulatory documents were used to analyse the study results: DSP 173-96 (1996); DSN 239-96 (1996); DSN 3.3.6.039-99 (1999); and DBN V.1.1-31:2013 (2013).

The equipment used in conducting field research of the impact of oil and gas production facilities on environmental components was purchased under the international project HUSKROUA/1702/6.1/0022CRIMIGE Regional Centre for Training and Monitoring of the Environmental Impact of Electrical Installations (2020) and equipment of the certified Educational and Scientific Laboratory “Physical and Chemical Methods of Environmental State Research” (2023) of the Department of Ecology of the Ivano-Frankivsk National Technical University of Oil and Gas (Certificate of Technical Competence No. IF 447 of 31.03.2023). The equipment allowed for a wide range of environmental studies (the country of manufacture of most devices is Germany): determination of meteorological parameters (air temperature, humidity, wind speed, illumination); air pollution (content of fine particles PM_{2.5-10}, concentration of carbon monoxide and formaldehyde, dew point temperature); water pollution (dissolved oxygen, pH, mineralisation); measurement of electric and magnetic fields, extended and long-term recording of all important parameters; noise measurement; vibration frequency measurement. The equipment allowed to determine the radiation background and identify radionuclides with an indication of the category to which they belong in accordance with the requirements of the International Atomic Energy Agency, including industrial radionuclides (⁵⁷Co, ⁶⁰Co, ¹³³Ba, ¹³⁷Cs, ¹⁹²Ir, ¹⁵²Eu and ²⁴¹Am) and natural radionuclides (⁴⁰K, ²²⁶Ra, ²³²Th, ²³⁸U and decay products). AZ-8603 autonomous portable water laboratory (4 in 1) was used in the research. Oximeter/pH meter/conductometer/salinity meter was used. ET-965 multifunctional device for assessing meteorological parameters was utilised to identify air temperature, humidity, wind speed, illumination. Air quality analyser CEM DT-9881 was used for determining the content of fine particles (dust), concentration of carbon monoxide and formaldehyde, dew point temperature. Electromagnetic radiation analyser NFA-400 is designed to measure the electrical and magnetic components, with the range of magnetic flux density measurement from 0.1 to 9.999 nT. Frequency analyser NFE-35C is designed to detect pulsed sources of electromagnetic radiation. Radiometer SPEKTRA MKS-11GN was used – a highly sensitive search dosimeter with the ability to computer plot the obtained spectra and record observation points on the

map. Vibrometer PCE-VT 3700S was also utilised. Thus, the surveys were conducted with modern European equipment and in accredited laboratories, which confirms the reliability of the results obtained.

✔ Results and Discussion

The main natural component that is adversely affected is atmospheric air. The process of oil and gas production at the Bytkiv-Babchenskyi Field is accompanied by emissions of pollutants into the air from the system of collection, treatment and transportation of well products from the field, which is represented by group units, a thermochemical unit and individual well collections. There is also a natural migration of gas from oil and gas-bearing formations to the Earth's surface, which is associated with the widespread development of fractures. This is the main reason for the gas pollution in the Pasichna and Bytkiv settlements. Meteorological and air pollution parameter studies were conducted near 8 oil and gas production facilities of the Bytkiv-Babchenskyi Field, some of which are shown in the photo (Fig. 1).

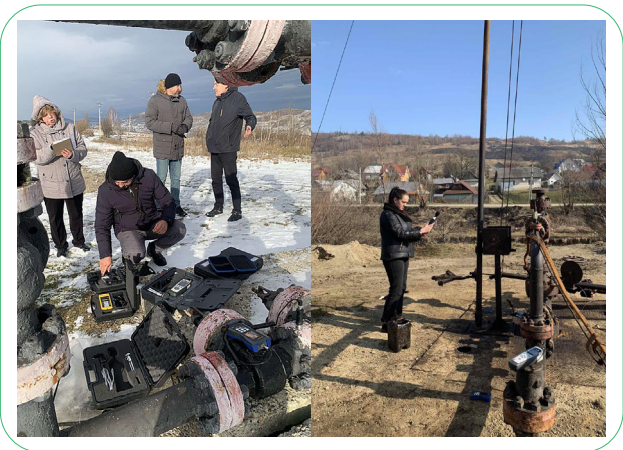


Figure 1. Conducting field research
Source: created by the authors

The main results of the field research of air pollution from oil and gas production facilities at the Bytkiv-Babchenskyi Field in 2022-2023 are presented in Table 1 and Table 2.

Table 1. Results of the study of air pollution from oil and gas production facilities at the Bytkiv-Babchenskyi Field, 2022

Indicator name	Oil and gas production facilities at the Bytkiv-Babchenskyi Field															
	Facility 1				Facility 2				Facility 3				Facility 4			
	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV
Air temperature, °C	+3.7	+20.4	+28.9	+0.8	+3.8	+20.5	+31.8	+0.9	+3.8	+20.2	+29.6	+0.2	+3.8	+22.5	+33.1	−0.9
Relative humidity, %	50.4	38.3	46.4	89	50.4	38.3	38.7	90.4	50.4	36.7	42.7	87	50.4	38.1	38.7	94.0
Wind speed, m/s	2.5	5.5	0.1	1.0	2.6	6.0	0.0	1.1	2.6	6.2	0.1	1.9	2.3	5.8	0.1	1.6

Table 1. Continued

Indicator name	Oil and gas production facilities at the Bytkiv-Babchenskyi Field															
	Facility 1				Facility 2				Facility 3				Facility 4			
	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV
Illumination, lux	0.54	10.5	12.8	0.21	0.47	10.9	33.3	0.27	0.51	10.7	36.2	0.45	0.54	10.8	38.7	0.24
CO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
HCHO	0.0	0.0	0.001	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.001	0.0	0.0	0.0	0.0	0.0
PM0.5-2.5	0.0	4	5	34	0.0	4	4	25	3	21	24	17	0.0	33	3.7	31
PM2.5-10	0.0	10	11	61	0.0	11	10	54	21	53	67	32	0.0	64	10	63

Source: created by the authors

Table 2. Results of the study of air pollution from oil and gas production facilities at the Bytkiv-Babchenskyi Field, 2023

Indicator name	Oil and gas production facilities at the Bytkiv-Babchenskyi Field															
	Facility 5				Facility 6				Facility 7				Facility 8			
	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV
Air temperature, °C	−3.2	+21.7	+28.9	23.3	−3.0	+21.7	+28.9	23.5	−2.1	+21.9	+28.9	23.5	−3.0	+21.9	+28.9	23.5
Relative humidity, %	65.7	37.1	46.4	58.7	63.3	37.1	46.4	60.0	57.1	38.5	46.4	60.0	62.7	38.5	46.4	60.0
Wind speed, m/s	0.8	0.3	0.1	0.6	1.5	0.3	0.1	0.8	1.3	0.1	0.1	0.2	1.7	0.1	0.1	0.2
Illumination, lux	1.7	9.7	12.8	0.31	1.7	9.5	13.1	0.3	3.3	10.8	14.1	0.2	3.3	11.5	15.2	0.28
CO	0.0	0.0	0.0	0.0	0.001	0.001	0.001	0.001	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
HCHO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PM0.5-2.5	5	4	5	3	3	2	2	2	9	9	8	7	4	4	5	3
PM2.5-10	8	8	11	9	9	8	8	9	17	15	15	12	8	8	10	7

Source: created by the authors

Thus, the results of the studies carried out in 2022-2023 on the state of atmospheric air near oil and gas production facilities in the vicinity of oil and gas production facilities in the Bytkiv-Babchenskyi Field show the following carbon monoxide emissions at most facilities are absent or do not exceed the MPC; the presence of formaldehyde in the air recorded near some facilities does not exceed the permissible hygienic standards; dust particles of PM 2.5-10 prevail in the air, which is associated with meteorological factors. O. Romaniuk (2023) described in detail the environmental impacts of oil and gas production and the problem of gas pollution in settlements on the example of Boryslav. S.N. Riddick *et al.* (2020) focused on methane air pollution in the areas of oil fields, which is especially relevant in the territory of old oil fields, where there are many abandoned wells. M. Gál-falk *et al.* (2021) proposed to explore such areas using

unmanned aerial vehicles with CH₄ gas detectors, which allows to map CH₄ concentration and wind speed with an accuracy of 0.84 parts per billion/s and 0.1 m/s, respectively, and is especially important in complex landscapes. P.M.B. Saint-Vincent *et al.* (2020) and A. Townsend-Small & J. Hoschouer (2021) have shown that gas concentrations are also affected by the season, so it is important to conduct continuous monitoring of well emissions throughout the year. In their research, J. Jońca *et al.* (2022) proved the influence of meteorological factors on the conditions of concentration and dispersion of hydrocarbon gases in the territory of oil fields. L. Makarenko (2024) showed that an increase in humidity reduces PM 2.5 pollution, while PM 10 pollution increases. And the pollution rate is largely influenced by the air exchange process. M. Hu *et al.* (2021) established a direct correlation between meteorological factors and the degree of air pollution.

Thus, most studies of the impact of oil and gas production on the air are related to the emanations of hydrocarbon gases, primarily methane. However, no studies have been conducted on the presence of other gases, such as formaldehyde and carbon monoxide, at oilfields. The results of the research show the presence of these gases near oil and gas production facilities, which requires further more detailed observations. However, the use of unmanned aerial vehicles with gas detectors is only appropriate when mapping areas with abandoned wells that may be a source of CH₄. Researchers have shown the influence of seasonal factors on the concentration of both methane and PM particles in the air. The study confirms the research of other scientists on the impact of meteorological parameters on the concentration of PM_{2.5-10}. During the monitoring of water bodies, express analysis was used using the AZ-8603 autonomous portable water laboratory (4 in 1) oximeter/pH-meter/satellite/TDS (Fig. 2). The results of the observations are presented in Table 3. For chemical analysis of water samples collected in the Bystrytsia Nadvirnianska River near Site 7, the Water Monitoring Laboratory of the Western region of the Dniester Basin Water Resources Administration determined the mass concentration of

elements, chemical and physicochemical indicators of water quality, and examined the content of volatile organic compounds, polyaromatic hydrocarbons, heavy metals, pesticides, pharmaceuticals, and elemental composition of water (Fig. 3).



Figure 2. Rapid water analysis
Source: created by the authors

Table 3. Results of rapid analysis of water samples from water bodies

Indicator name	Bystrytsia Nadvirnianska River near Site 6	Bystrytsia Nadvirnianska River near Site 7	Hygienic water quality standards	Code of regulatory documents
Hydrogen index, pH	6.4	7.0	6.5-8.5	DSTU 4077-2001 (2002)
Mineralisation, mg/dm ³	51.5	478	1,000	DSPN 2.2.4-171-10 (2010)
Dissolved oxygen, mg O ₂ /dm ³	30	12	> 4.0	DSTU ISO 5813:2004 (2004)
Temperature, °C	12.2	13.4		

Source: created by the authors

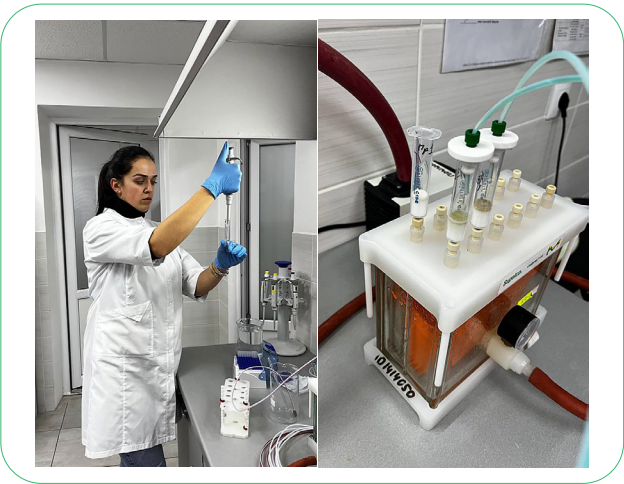


Figure 3. Sample preparation and analysis of water samples in the certified laboratory of the Dniester Basin Water Resources Administration
Source: created by the authors

The following conclusions can be drawn based on the results of the water sample analysis. In terms of salt content, the water is slightly mineralised, the water hardness is 4.7 mg-eq/dm³ with an upper limit of 7.0 mg-eq/dm³, the calcium content is 71 mg/dm³, the bicarbonate content is 305 mg-eq/dm³, and the water is bicarbonate. Chromatographic tests from the List 45+ according to the Law of Ukraine No. 45 (2017), the water sample contained volatile organic compounds such as benzene, dichloromethane, hexachlorobutadiene, and the concentrations of these pollutants did not exceed environmental quality standards. The content of biogenic elements, namely nitrogen, which is present in the form of inorganic compounds – ammonium ions, nitrate ions, is very low, and the content of phosphorus, in the form of orthophosphates and nitrites, is not detected, the concentration of biogenic elements is insignificant. The elemental composition is characterised by the presence of argentum, iron, manganese, nickel, molybdenum, potassium, sodium, zinc, vanadium, phosphorus, sulfur, titanium, lithium, stibium, barium, selenium and boron,

which are detected in insignificant concentrations that do not exceed the MPC, and therefore can be considered as trace elements. Among the toxic elements, strontium was detected in the water sample, with a content equal to the MPC. Toxic metals – cadmium, lead, arsenic and mercury – are absent. According to the results of chemical and physico-chemical indicators, the water is clean. The studies have not revealed any negative impact of oil and gas production facilities on the hydrosphere.

Research on the Bystrytsia Nadvirnianska River is related to the following main areas. A. Mkrtchian & I. Kovalchuk (2023) established the regularity of seasonal differentiation of the influence of certain factors and landforms on the temperature regime of the river. O.V. Lototska & V.O. Prokopov (2021) studied the water quality indicators of the Bystrytsia Nadvirnianska River within the Cherniiv Village of the Ivano-Frankivsk territorial community by such indicators as dissolved oxygen, ammonium ion, phosphate ion, chemical oxygen consumption, biochemical oxygen consumption, iron and manganese content, which correlates with the studies of the Bystrytsia Nadvirnianska River within the settlements of Pasichna and the southern part of Bytkiv. Since the oil and gas production facilities of the Bytkiv-Babchenskyi Field are located near the Bystrytsia Nadvirna River with its numerous tributaries flowing through the territory of the settlements, the study of water quality indicators is important to prevent possible pollution of water bodies. However, no studies have been conducted on the impact of oil and gas production facilities on water quality indicators within the Carpathian Region. There is also no information on seasonal fluctuations in the

physicochemical and chemical parameters of water. Therefore, research in terms of monitoring the chemical and physicochemical water quality indicators of the Bystrytsia Nadvirnianska River within the impact of oil and gas production in the Bytkiv-Babchenskyi Field is relevant both from a practical and scientific point of view.

Visual examination of soil samples collected around oil and gas production facilities 1-8 showed that the soils are of the sod type with a low percentage of mechanical fractions. The soils are of the accumulative type, formed under unfavourable conditions by the humus-accumulative (sod) soil formation process. According to the results of the laboratory tests, it was found that the soils at the Bytkiv-Babchenskyi Field are characterised by very high and high organic matter content, with the content of 6.40% and 4.97% respectively, and high and medium levels of the sum of absorbed bases, the content of ammonium and nitrate nitrogen is medium, the content of mobile phosphorus compounds is low and medium, and the content of mobile iron compounds is very low. The low content of water-soluble sulphates is positive and indicates low soil salinity. The reaction of the soil solution is close to neutral. The pH value of the soil in the express analysis was in the range of 6.8-8.0. There are fluctuations in the pH value around oil and gas production facilities within ± 0.5 , which is most likely due to the shape of the relief. No oil contamination of soils around oil and gas production facilities is observed. For the purpose of controlling the physical and chemical characteristics of the soil, samples were taken in the vicinity of oil and gas production facilities 2 and 3. The results of the physical and chemical studies are presented in Table 4.

Table 4. Results of physical and chemical studies of soil samples collected near oil and gas production facilities 2 and 3

Indicators	Results of soil examination near oil and gas production facilities	
	Object 2	Object 3
Hydrogen pH, pH units	5.72	6.45
Hydrolytic acidity, mmol/100 g of soil	2.92	1.98
Mass percentage of organic matter, %	4.97	6.40
Mass proportion of ammonium nitrogen, mg/kg soil	13.4	13.0
Mass proportion of nitrate nitrogen, mg/kg soil	10.0	5.0
Mobile phosphorus compounds (Kirsanov), mg/kg soil	70	37
Exchangeable calcium, mmol/100 g of soil	10	12.2
Exchangeable magnesium, mmol/100 g of soil	2.9	3.2
Sum of absorbed bases, mmol/100 g of soil	13.3	15.8
Mass concentration of water-soluble sulphates, mg/kg soil	21	31
Mobile iron compounds, mg/100 g of soil	0.52	0.48

Source: created by the authors

The studied soil samples are characterised by very high and high organic matter content, with values of 6.40% and

4.97% respectively, and high and medium levels of total absorbed bases. The soil solution reaction (pH) is neutral

and close to neutral. The content of ammonium and nitrate nitrogen is average and almost the same in both samples. However, these samples have low to medium levels of mobile phosphorus and very low levels of iron compounds. The content of water-soluble sulphates is also low, which is positive and indicates low soil salinity. The main areas of research on soil pollution and degradation in the areas of oil fields are the effects of oil pollution, the study of the processes of chemical elements migration in soils, bioindication and bio-reclamation. V. Lopushniak & H. Hrytsuliak (2021) in their research on the territory of the oil and gas pipeline in Bytkiv Village, Nadvirna District, concluded that heavy metals contained in oil that falls on the surface are migrating in the soil-plant system. E.C. Nwadike *et al.* (2020) investigated the effects of soil contamination by crude oil and its impact on microbial activity, and H. Gao *et al.* (2022) on the soil ecosystem. Changes in the physical and chemical properties of soils will also affect the quality of vegetation. Research by L. Yuan *et al.* (2022) on vegetation degradation due to oil impacts near wells showed that such a negative impact is observed at a distance of up to 40 m from the well and that the number of plants and their resilience decrease. As noted by O. Orlov & M. Rahulina (2023), the soils of the Bytkiv-Babchenskyi Field area are diverse in origin and properties, and are characterised by a diverse soil cover. The conditions of relief influence on soil cover formation were studied by A. Yavorska & Z. Pankiv (2022) and Z. Pankiv & P. Honcharuk (2023). B. Karpinskyi (2023) stated that no studies have been conducted in the Carpathian Region to determine the level of soil oil contamination due to filtration processes. The results of the study by A.V. Pukish *et al.* (2021) on soil contamination by hydrocarbons in the process of oil and gas production show that there are changes in the physical, chemical and mechanical properties of soils. This results in a decrease in water permeability and moisture capacity, as well as deterioration of aeration and temperature balance. The research has established a correlation between salinity types and the concentrations of phosphorus and alkaline-hydrolysed nitrogen, phosphorus, potassium and humus. Ya. Semchuk *et al.* (2021)

studied the impact of oilfields on the pollution of ground-water, surface water, and soil by formation water. According to the scientists, the consequences of such pollution can have a greater negative impact than the penetration of oil into the soil. V. Sierohlazov & V. Yurchenko (2021), based on the results of microbiological and hydrochemical studies of produced water from oil production facilities, established the conditions for the development of sulfate reductions, as well as the dependence of dissolved oxygen and hydrogen sulfide. Also, as a result of formation water reaching the surface exposed during oil and gas production, soil salinisation occurs. It was found by R.C. Dalal *et al.* (2021) that increased mineralisation can lead to instability of organic carbon and nitrogen in soils.

The main areas of research into the impact of oil and gas production on soils are the migration of chemical elements and their influence on the condition, diversity and resilience of vegetation. Other studies focused on oil contamination of soils and its consequences. A relevant area of research is the impact of formation water on the soil cover, which leads to geochemical anomalies, soil salinisation and soil degradation. However, an important and unexplored area of research is the development of soil degradation processes, which can be caused by various mechanical or physical factors that destroy the integrity of the soil cover. This process is not so pronounced in time compared to the consequences of direct oil or highly mineralised formation water entering the surface. To do this, it is necessary to begin by determining the main physical and chemical parameters of soils near oil and gas production facilities. No such studies have been conducted on the impact of oil and gas production facilities on the soil cover in the Carpathian Region, and in particular the Bytkiv-Babchenskyi Field. The study of the impact of anthropogenic physical fields in the vicinity of oil and gas production facilities included the determination of electromagnetic, noise, vibration and radiation field parameters. The results of the study of anthropogenic physical fields in the vicinity of oil and gas production facilities at the Bytkiv-Babchenskyi Field are presented in Table 5.

Table 5. Results of measuring anthropogenic physical fields in the vicinity of wells

Quarter	Noise field	Vibration field	Radiation field		Electromagnetic field			
	Noise, dB	Vibration, μm	Radiation background, μSv/h	Radionuclides	The electrical component, V/m	Magnetic component, mG		
						X	Y	Z
Site 1								
III	45	25.1	0.07	not detected	48	44	0.7	–
IV	52	28.7	0.07	not detected	43	96	102	73
Site 2								
III	50.8	25.0	0.08	Ra ²²⁶	0.9			
IV	47.3	24.5	0.08	Ra ²²⁶	1.0	48	52	56
Site 3								
III	53.8	51.3	0.07	not detected		102	96	37
IV	72.1	96.1	0.09	not detected	49.6	155	193	119

Table 5. Continued

Quarter	Noise field	Vibration field	Radiation field		Electromagnetic field			
	Noise, dB	Vibration, μm	Radiation background, μSv/h	Radionuclides	The electrical component, V/m	Magnetic component, mG		
						X	Y	Z
Site 4								
III	44.1	28.7	0.07	not detected	14.9	137	482	91
IV	50.4	24.1	0.07	not detected	15.1	161	515	135
Site 5								
III	64.8	43 ¹ /34 ³ /24 ⁴ /23 ⁵	0.07	Ra ²²⁶	1.1	360	238	960
IV	67	41.5	0.08	Ra ²²⁶	1.1	149	155	167
Site 6								
II	36 ¹ /65 ² /43 ⁴	26 ¹ /36 ³ /34 ⁴ /27 ⁵	0.1	not detected	2.6	42	34	42
IV	40	29	0.1	not detected	2.0	37	39	41
Site 7								
II	74 ¹ /56 ²	23.0	0.09	Th ²²⁸ , Am ²⁴¹ ,	1.9	92	80	75
IV	70 ¹ /60 ²	164 ¹ /71 ³ /65 ⁴ /44 ⁵	0.09	Cs ¹³⁷ , Ir ¹⁹²	1.7	87	85	77
Site 8								
II	50.3	23.0	0.08	Co ⁶⁰ , Cs ¹³⁷ , Mo ⁹⁹ , Th ²³² , I ²¹³	1.1	155	161	215
IV	51	24 ¹ /23 ³ /23 ⁴	0.08	Co ⁶⁰ , Cs ¹³⁷ , Mo ⁹⁹ , Th ²³² , I ²¹³	1.1	151	158	203

Note: ¹ – normal operation mode; ² – during well blowing, pressure 85 atm; ³ – at a distance of 1 m; ⁴ – at a distance of 2 m; ⁵ – at a distance of 3 m
Source: created by the authors

During the radiation field survey, a spectrum of radionuclides was recorded at each monitoring point. The results of radiation field observations at the monitoring point near facilities 6 and 7 of the Bytkiv-Babchenskyi Field are presented in Figure 4 and Figure 5.

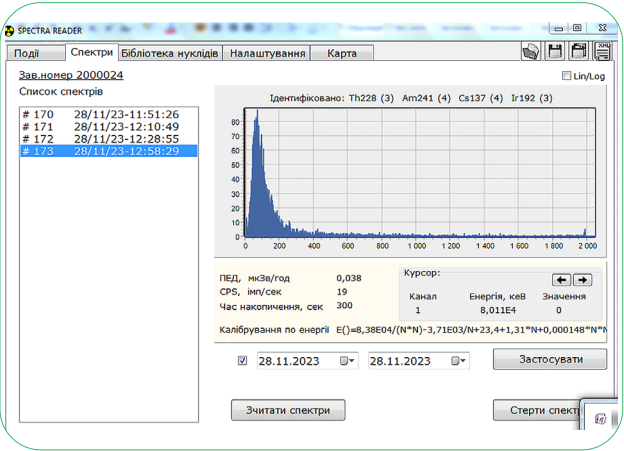


Figure 4. Spectra of radionuclides in the vicinity of the Site 6
Source: created by the authors

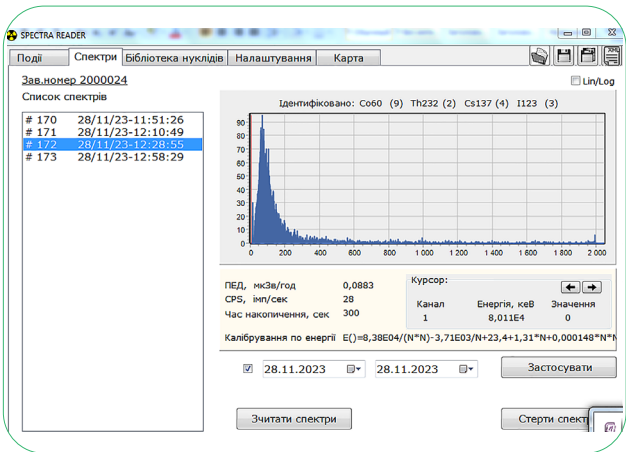


Figure 5. Spectra of radionuclides in the vicinity of the Site 7
Source: created by the authors

Thus, based on the results of studies of anthropogenic physical fields near oil and gas production facilities in 2022-2023, the following conclusions were drawn. The radiation background is in the range of 0.07-0.1 $\mu\text{Sv/h}$, which did not exceed the permissible standards, and there

was no anthropogenic radiation field in the study area. Noise pollution around the well was in the range of 36-72 dB, reaching its maximum value near the production wells, which is associated with the operation of the rocking machine and well blowdown. Vibration pollution near the wells had minimum values in the range of 23-29 microns, and the maximum value was reached near the production wells due to the operation of the rocking machine, but at a distance of 3 m the vibration reached a value of approximately 23 microns; the vibration level did not exceed the permissible standards, and an increase in vibration was also observed during well blowdown. The level of electromagnetic field did not exceed the permissible standards, and in most cases was generated by power lines passing through the study area; the oil and gas production facilities themselves are not sources of electromagnetic anthropogenic physical fields. Technogenic physical fields, namely vibration and noise, generated by the oil and gas production process have a local minor impact on environmental components.

Therefore, environmental problems arising in the area of oil and gas production may be of natural and man-made origin. The field development process may provoke an aggravation of the environmental situation due to the natural processes of hydrocarbon emanation, due to the tectonic structure of the Bytkiv-Babchenskyi Field. The study of the consequences of negative impact on environmental components is especially relevant in connection with the nature reserve fund objects located on the field development territory or in the immediate vicinity of the field, as well as due to the location of oil and gas production facilities in the territory of settlements. All components of the environment are subject to technological impact. The main areas of research into the environmental impact of oil and gas production facilities are related to air emissions, pollution of water bodies and soil with oil and highly mineralised reservoir water. Many research papers by scientists from neighbouring countries that were mentioned above have been devoted to such studies. However, it is the comprehensive monitoring of the environmental situation near oil and gas production facilities that is important. Certain technological processes of oil and gas production, such as well blowout or operation of a rocking machine, create a certain man-made impact due to the formation of artificial physical fields (acoustic, vibration and radiation) around such facilities. The parameters of such fields, their distribution and impact on various natural components have not been studied. The obtained research results have shown their importance and prospects for further study of the impact of oil and gas production processes and facilities on the environment.

✓ Conclusions

Based on the results of the atmospheric air condition research in the vicinity of oil and gas production facilities located on the Bytkiv-Babchenskyi Field territory, it was established that carbon monoxide emissions near Object 6

exceeded the established standards. The presence of PM 2.5 (10) dust particles in the air is related to meteorological factors. Soils at the Bytkiv-Babchenskyi Field are characterised by a high content of organic matter. The low content of water-soluble sulphates indicates low soil salinity. The reaction of the soil solution in the rapid analysis was in the range of 6.8-8.0. There was a fluctuation in pH around oil and gas production facilities within ± 0.5 , which is most likely due to the relief shape. No oil contamination of soils was observed. According to the results of chemical and physicochemical parameters, the water in rivers and streams is clean. Concentrations of volatile organic compounds did not exceed environmental water quality standards, the content of biogenic elements was very low, phosphorus content was not detected, water hardness was 4.7 mg-eq/dm³, and the water was hydrocarbonate with a calcium content of 71 mg/dm³.

In the vicinity of the oil and gas production facilities, the authors conducted studies of man-made physical fields: radiation, noise, vibration and electromagnetic. The research results showed that the radiation background was within 0.07-0.1 μ Sv/h and did not exceed the permissible standards; noise pollution around the well was within 36-72 dB, vibration pollution near the wells had minimum values within 23-29 microns, and the increase in noise and vibration fields is associated with the operation of the rocking machine and well blowdown, the level of electromagnetic field did not exceed the permissible standards, and its parameters are associated with power lines. Thus, no negative impact of oil and gas production facilities on natural objects in the territory of the Bytkiv-Babchenskyi Field was detected.

Analysing the results of the research on the impact of oil and gas production facilities on environmental components and taking into account the main areas of scientific research on related issues, the following recommendations can be made for planning research areas: man-made physical fields, namely noise and vibration, require a larger-scale research to reasonably assess the impact of the oil and gas production process as a possible negative factor; the impact of man-made physical fields arising in the course of relevant oil and gas production operations on flora and fauna; gas pollution from abandoned wells in the Carpathian Region; the impact on the soil cover of possible hydrocarbon manifestations from abandoned wells in the Carpathian Region; natural and man-made gas pollution in the Bytkiv and Pasichna settlements.

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✓ Conflict of Interest

None.

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Екологічні наслідки видобування нафти і газу на прикладі Битків-Бабченського нафтогазового родовища

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✔ **Анотація.** Більшість технологічних процесів створюють техногенне навантаження на навколишнє середовище – не винятком є нафтогазовидобувна галузь. Через нафтогазовидобування на площі Битків-Бабченського родовища спостерігається загазованість території населених пунктів Пасічна і Битків, витоки нафти на денну поверхню, проте, необхідно прагнути мінімізації негативного впливу та збереження довкілля. Метою дослідження було проведення комплексного аналізу екологічного стану атмосфери, ґрунтів, гідросфери та техногенних фізичних полів (радіаційного, шумового, вібраційного, електромагнітного) поблизу різних об'єктів нафтогазовидобування Битків-Бабченського родовища для визначення техногенного впливу процесу видобування нафти й газу. Використовувалися такі методи: спостереження, вимірювання показників довкілля, метеорологічних параметрів та параметрів фізичних полів, лабораторні методи аналізу. Використано широкий спектр сучасних приладів, який дозволяє проводити експрес-аналіз та визначати параметри фізичних полів. У лабораторних умовах проводився більш детальний аналіз проб води та ґрунтів із використанням фізико-хімічних методів аналізу. Визначені хімічні, фізико-хімічні показники якості води, вміст летких органічних сполук, поліароматичних вуглеводнів відповідали нормативним показникам. З токсичних елементів виявлено стронцій, вміст якого не перевищував гранично допустиму концентрацію. За вмістом солей вода гідрокарбонатна слабомінералізована. Ґрунти низькозасолені з нейтральним рН ґрунтового розчину. Вміст рухомих сполук заліза, фосфору, азоту, відповідно, дуже низький, низький і середній, а органічної речовини – дуже високий. Встановлено, що параметри техногенних фізичних полів не перевищують допустимих норм. Результати дослідження показали, що техногенний вплив процесу нафтогазовидобування на атмосферне повітря, водні об'єкти та ґрунти знаходиться у межах допустимих норм. Практичне значення отриманих результатів полягає у комплексному спостереженні протягом року за станом природних об'єктів, що є важливим для фахівців нафтогазової галузі під час оцінки впливу об'єктів нафтогазовидобування на довкілля та розробки природоохоронних заходів

✔ **Ключові слова:** нафтогазова галузь; техногенні фізичні поля; фізико-хімічні дослідження; загазованість; атмосферне повітря; ґрунти; об'єкти гідросфери



Monitoring studies of the ecological and hydrogeochemical situation in the zone of influence of technogenic objects of the mining and industrial complex of the Kalush-Holyn Potash Deposit

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✓ **Abstract.** The assessment of groundwater and surface water conditions in areas of depleted salt deposits is a crucial component of monitoring studies due to the significant anthropogenic impact of objects such as tailings ponds, sludge accumulators, and the Dombrovskiy Quarry. The aim of the study was to establish, based on real experimental data from hydrogeochemical analyses of long-term groundwater monitoring via a network of hydrogeological observation wells, the areas of groundwater salinisation in the Kalush mining and industrial region, to assess the dynamics of chemical and physico-chemical indicators, and to identify threats to the region's ecological situation. The research stages included the systematisation of monitoring data for 2021-2023, the creation of digital cartographic layers and attribute databases with quantitative data on groundwater chemical composition, geoinformation modelling, and the development of salinisation maps of the Kalush mining and industrial region and the dynamics of the aquifer salinisation. In 2023, hydrogeochemical studies were conducted in the Kalush mining and industrial region with the collection of 25 samples from observation wells, the Dombrovskiy Quarry, sludge accumulators, and the Limnytsia River. Water mineralisation and chemical composition were analysed. The study results showed the highest levels of mineralisation in the waters of sludge accumulator No. 3 and tailings pond No. 2, where mineralisation levels exceeded maximum allowable concentrations by

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140 and 110 times, respectively. Chloride and sulphate contents in these objects also significantly exceeded permissible standards. A comparison of data for 2022 and 2023 revealed a significant increase in pollutant concentrations in several wells, confirming the continued negative impact of anthropogenic objects. Meanwhile, water quality in the Limnytsia River remained stable. The value of the study lies in evaluating the environmental condition of groundwater in the Kalush mining and industrial region based on the systematisation of hydrogeochemical monitoring data through observation wells using geoinformation modelling approaches

✔ **Keywords:** depleted salt deposits; observation wells; groundwater; geoinformation system; modelling

✔ Introduction

Depleted potash and rock salt deposits frequently create a complex environmental situation with a range of ecological challenges. In Ukraine, notable examples include the Stebnyk, Kalush-Holyn, and Solotvyno salt deposits. Key environmental issues arising from these sites include soil and water contamination, surface subsidence, collapses above mines, disruption of the groundwater and surface hydrosphere regimes, the generation of mining waste in the form of tailings ponds and sludge storage facilities, erosion and land degradation, as well as biodiversity loss. These environmental problems resulting from salt deposit exploitation have been extensively documented in scientific research.

Y. Khomyn *et al.* (2019) identified the environmental risks associated with highly mineralised saline brines and proposed their disposal using depleted hydrocarbon extraction wells. Additionally, researchers V. Dyakiv (2022) and I.Ya. Sapuzhak (2023) examined the issue of activated subsidence and collapse phenomena in depleted salt deposits. These phenomena arise from the voids formed after raw material extraction via underground mining methods. Abandoned mines can collapse, causing ground surface subsidence and posing significant risks to infrastructure and human safety.

The hydrogeological situation plays a crucial role in the environmental challenges associated with depleted salt deposits, often exacerbated by the intrusion of groundwater into mining workings. E.D. Kuzmenko *et al.* (2018; 2020) explored the application of geodetic and geophysical monitoring over abandoned underground workings to forecast surface subsidence dynamics. They proposed a comprehensive research framework enabling the prediction of deformation processes. Similarly, A. Zhang *et al.* (2018) and M. Pakshyn *et al.* (2020) examined deformation processes above depleted mine workings using remote sensing data, particularly radar interferometry. P. Zhurnov *et al.* (2021) classified zones prone to hazardous natural and anthropogenic processes within the influence areas of mining infrastructure in the Kalush-Holyn Potash Deposit.

Groundwater regime disturbances, including the inflow of freshwater and intensified water exchange, can activate hazardous exogenous geological processes, notably karst phenomena. Monitoring and modelling the progression of these processes are vital for predicting their activation. Furthermore, L. Davybida *et al.* (2020) and A. Stroj *et al.* (2020) emphasised the significant influence of groundwater

regime dynamics on the development of hazardous geological processes. Mining waste, containing residual salts and other chemicals, poses additional environmental risks. Improper storage and exposure to atmospheric factors can lead to environmental contamination. C. Li *et al.* (2020) and A. Zaryab *et al.* (2021) highlighted the increased salt concentrations in surface and groundwater as a major threat. This escalation significantly deteriorates water quality, potentially causing water supply issues for local communities and adversely affecting aquatic ecosystems.

Most large potash salt deposits face similar environmental challenges, including water and soil contamination, land erosion, the formation of underground cavities, and biodiversity loss. Assessing the condition of groundwater and surface water in areas associated with both active and depleted mineral deposits is a critical component of comprehensive monitoring studies. Such evaluations enable the tracking of mining activities' impacts on the hydrological situation, ensuring the timely detection of changes in water composition and potential environmental threats. Given that mining operations or the closure of deposits can significantly influence the surrounding environment, monitoring provides essential data for the development of conservation measures aimed at minimising risks to water quality, public health, and the overall ecological stability of the region. This research focused on assessing the dynamics of chemical and physicochemical indicators and the potential threats to the environmental situation in the area. The primary objective was to identify zones of groundwater salinisation in the Kalush mining and industrial district, based on real experimental data obtained from long-term hydrogeochemical monitoring conducted through a network of hydrogeological observation wells.

✔ Materials and Methods

Annual environmental monitoring is conducted in the Kalush mining and industrial district to assess the salinity levels of surface and groundwater, as well as the subsidence zones above the former Kalush, Holyn, and Novo-Holyn mines. Particular attention is given to Quaternary aquifers, which serve as sources of drinking water for the local population. Quaternary deposits in the area include deluvial sediments, Lower Quaternary alluvial deposits, Middle Quaternary alluvial deposits, Upper Quaternary alluvial deposits, and modern alluvial deposits. The study involved hydrogeochemical investigations through a network of

observation wells, geodetic monitoring of land subsidence, and geophysical surveys to identify potential zones of subsidence and surface collapse. In the QGIS environment, the inverse distance weighting (IDW) interpolation method was used to analyse data and create cartograms. Using QGIS and GRASS GIS modelling modules, maps were generated to visualise changes in salinity and concentrations of specific substances in the observation wells across the Kalush mining and industrial district.

To monitor salinisation zones and determine the degree of groundwater salinity, wells equipped with Ukrainian-made filters capable of sampling from the first aquifer were utilised. This aquifer comprises gravel deposits, lies at depths ranging from 0.5 to 13 m, and has a thickness of several to 12 m. Groundwater sampling for hydrogeochemical monitoring was performed through a network of observation wells. Most of these wells – 20 in total – were installed in 2019 by Noosphere LLC, although some of them are no longer operational. Additional samples were collected

from wells established during the operational period of the Kalush Potash Plant.

The water sampling methodology from observation hydrogeological wells followed standard procedures to obtain representative and accurate data on groundwater composition. The primary steps of the sampling process included the preliminary cleaning of the well by pumping out three volumes of water. This ensures the collection of fresh, non-stagnant water, which better reflects the current state of the groundwater aquifer. A valve-type sampler was used for the collection of samples. In 2023, samples were taken from 19 observation wells in the monitoring hydrogeological network of the Kalush mining and industrial district, as well as from hazardous technogenic objects, including the salinisation zones of the groundwater aquifer – such as the Dombrovskiy Quarry, tailings pond, tailings dam No. 2, drainage trench, and the Limnytsia River. A total of 25 samples were collected. The locations of the objects from which the samples were taken are shown in Figure 1.

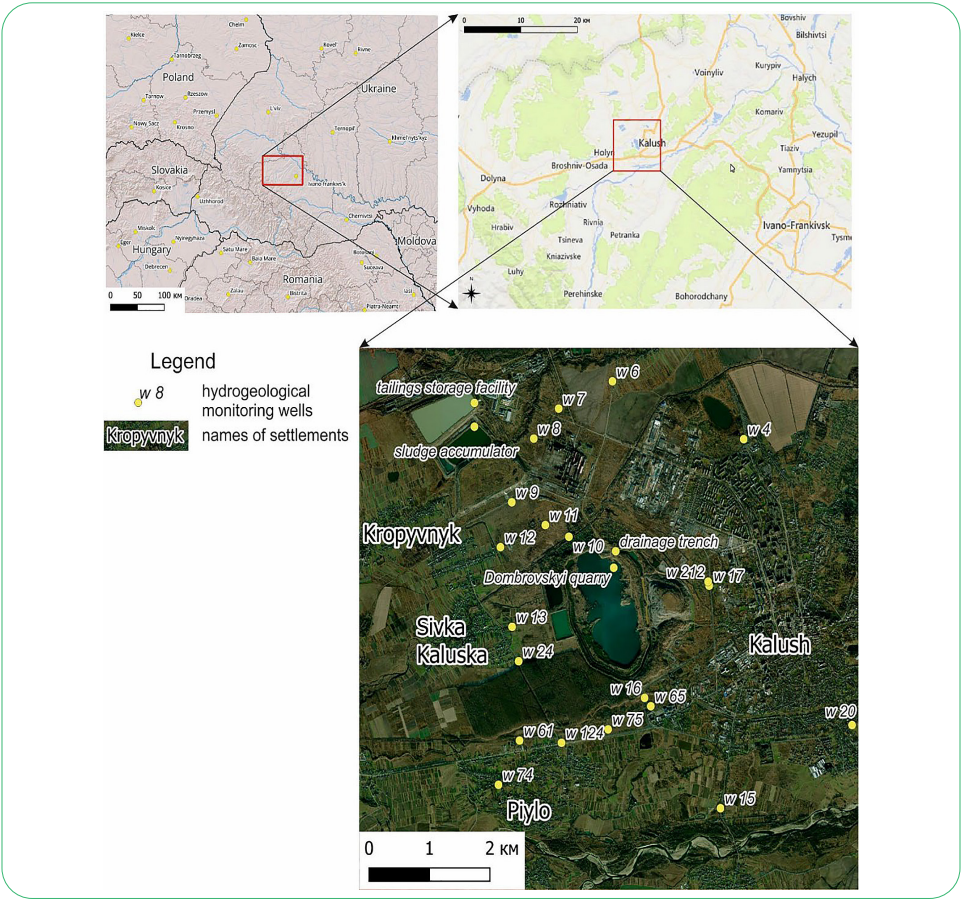


Figure 1. Cartogram of the study area and the network of observation wells
Source: developed by the authors based on ArcGIS (n.d.), Bing Maps (n.d.), Google Maps (n.d.)

Chemical and physicochemical indicators, including the content of salts and chlorides, were determined in the samples. These indicators are crucial for assessing the condition of the water, as highly mineralised waters and runoff may penetrate groundwater aquifers and the Limnytsia River,

which serves as a source of drinking water for the city of Kalush and flows into the Dniester River, a transboundary waterway. The analysis of the test results was carried out in accordance with the hygienic standards approved by Order of the Ministry of Health of Ukraine No. 721 (2022). The

determination of chemical and physicochemical parameters was performed at the water monitoring laboratory of the Western Region of the Dniester River Basin Water Resources Authority using the following instruments: Ulab 102 HD spectrophotometer (China), Horiba Ltd Laguna-pH meter PC 1100 (Japan), and Horiba Ltd Laguna-conductometer PC 1100 (Japan).

✓ Results and Discussion

The results of the study confirmed a high salt content in the sludge reservoir, tailings pond, and Dombrovskiy Quarry. With the maximum allowable concentration (MAC) of salts in water set at $1,000 \text{ mg/dm}^3$, the mineralisation levels of the water in tailings pond No. 3 were found to be 140 times higher than the norm, reaching $140,800 \text{ mg/dm}^3$; in tailings pond No. 2, it was nearly 110 times the norm at $110,840 \text{ mg/dm}^3$; and in the Dombrovskiy Quarry, it was almost 20 times the norm at $19,600 \text{ mg/dm}^3$. The qualitative composition of the water is characterised by the presence of chloride and sulfate salts. With standard values of chlorides at 350 mg/dm^3 and sulfates at 500 mg/dm^3 , the samples taken from tailings pond No. 2, the sludge reservoir, and the Dombrovskiy Quarry showed exceedances of the established MAC. Chloride concentrations exceeded the MAC by 110.4, 147.3, and 25.6 times, respectively, and sulfate concentrations by 26.2, 42.4, and 3.9 times. These indicators were also high in the drainage trench, where mineralisation exceeded the MAC by 3.8 times, chloride content by 3.7 times, and sulfate content by 1.3 times. The ionic composition of the water clearly shows higher than the standard values of calcium and magnesium salts.

The study of the samples taken from the wells in the Kalush district revealed that the highest concentrations of salts were found in well No. 9: the mineralisation level was $59,900 \text{ mg/dm}^3$, sulfates were $14,900 \text{ mg/dm}^3$, chlorides were $21,766 \text{ mg/dm}^3$, calcium was $1,804 \text{ mg/dm}^3$, and magnesium was $1,798 \text{ mg/dm}^3$. Additionally, in five samples, the sulfate content ranged from $1,351 \text{ mg/dm}^3$ in well No. 8 to $6,419 \text{ mg/dm}^3$ in well No. 13, exceeding the MAC by 2.7 to 12.8 times, respectively. Chloride levels exceeding the MAC were recorded in five samples, with the highest concentration found in well No. 65 at $13,542 \text{ mg/dm}^3$, which is 38.7 times the norm. The lowest chloride concentration was found in well No. 6 at 16 mg/dm^3 . In 13 samples (No. 4, 6, 7, 10, 12, 15, 17, 20, 24, 61, 74, 75, and 212), the salt, sulfate, and chloride levels were within the MAC limits. In four samples, the calcium and magnesium content exceed the standard values of 200 mg/dm^3 and 50 mg/dm^3 , respectively. In sample No. 8, the calcium content is 523 mg/dm^3 , which is 2.6 times the MAC. In sample No. 11, the calcium content is $1,209 \text{ mg/dm}^3$, which exceeds the MAC by 6 times, and magnesium is $1,067 \text{ mg/dm}^3$, exceeding the MAC by 21.3 times. In sample No. 13, calcium is 303 mg/dm^3 , which is 1.5 times the MAC. In sample No. 65, calcium is $1,230 \text{ mg/dm}^3$, which

exceeds the MAC by 6.2 times, and magnesium is 533 mg/dm^3 , exceeding the MAC by 10.7 times.

Biogenic elements – ammonium ions, nitrites, nitrates, and orthophosphates – were also analysed. The results confirmed contamination with biogenic elements in the tailings pond No. 2 and the sludge reservoir, where ammonium ion concentrations exceeded the MAC by 3.7 and 2.1 times, respectively, and nitrate ions in the sludge reservoir exceeded the MAC by 1.3 times. Among the wells, ammonium ion concentrations exceeded the MAC in three samples: No. 9, 11, and 13. Ammonium ion concentrations ranged from 0.52 mg/dm^3 in sample No. 124 to 29 mg/dm^3 in sample No. 13, which is 11.3 times the MAC, 22 mg/dm^3 in sample No. 11 (8.6 times the MAC), and 9.3 mg/dm^3 in sample No. 9 (3.6 times the MAC). No exceedance of the MAC for nitrite ions was found in any sample, and only one sample, No. 9, showed an exceedance for nitrate ions (1.5 times the MAC).

Toxicological indicators, including manganese, iron, chromium, and copper, were measured. In tailings pond No. 2 and sludge reservoir No. 3, manganese concentrations exceeded the MAC by 3.3 and 80 times, respectively. Iron concentrations in tailings pond No. 2 were 21 times the MAC and in sludge reservoir No. 3, 2 times the MAC. In well samples, manganese concentrations exceeded the MAC in 10 samples. In 4 of these, the exceedance was slight, with manganese levels ranging from 0.13 mg/dm^3 (1.3 times the MAC) in sample No. 75 to 20 mg/dm^3 in sample No. 65, which is 200 times the MAC. The highest manganese content was observed in sample No. 13, at 5.7 mg/dm^3 , which exceeds the MAC by 57 times. The iron content is high in 13 samples – No. 4, 6, 7, 9, 10, 11, 13, 16, 17, 61, 65, 124, and 212 – ranging from 0.36 mg/dm^3 in wells No. 17 and 212 (1.2 times the MAC) to 65 mg/dm^3 in well No. 65 (217 times the MAC). The iron content in sample No. 61 is high at 18 mg/dm^3 , exceeding the MAC by 60 times. No exceedance of the MAC for chromium and copper was detected in well samples.

Testing of a sample from the Limnytsia River for mineralisation, according to V. Khilchevskiy's classification, confirms that the water is moderately fresh and soft, with a chemical composition of bicarbonate-sulfate. The salinity indicators are low and have remained almost unchanged over an extended observation period. The concentrations of biogenic and toxicological elements are within normal ranges. In 2023, laboratory chemical analyses were conducted on samples taken from the monitoring well network, with the same structure as in 2022, except for the determination of metals using spectrometric methods. To evaluate the dynamics of substance concentrations in the water, it is necessary to systematise and compare the obtained results from 2022 and 2023. The values of mineralisation and salt composition for 2022 and 2023, along with their differences (as a measure of dynamics), are presented in Table 1.

Table 1. Mineralisation of water samples

No.	Indicator	Mineralisation, mg/dm ³			
Sampling location		Test results			
		2021	2022	2023	Δ
1	Tailings Pond No. 2	83,916		110,840	
2	Sludge Accumulation Pond	80,356		140,800	
3	Drainage Trench		2,604	3,780	1,176
4	River Limnytsia		189	199	10
5	Dombrovskiy Quarry	20,320	24,829	19,600	−5,229
6	No. 3	783	747		
7	No. 4	335	497	662	165
8	No. 5	1,347	1,072		
9	No. 6	1,197	504	232	−272
10	No. 7	422	345	220	−125
11	No. 8	3,810	4,421	2,890	−1,531
12	No. 9	23,746	18,164	59,900	41,736
13	No. 10	1,227	3,764	692	−3,072
14	No. 11	1,680	8,474	26,400	17,926
15	No. 12	630	649	359	−290
16	No. 13	2,908	5,199	16,023	10,824
17	No. 15	292	264	297	33
18	No. 16	3,859	8,465	1,740	−6,725
19	No. 17	998	886	676	−210
20	No. 19	2,626	4,183		
21	No. 20	443		330	
22	No. 24		495	381	−114
23	No. 61			852	
24	No. 65			29,211	
25	No. 74			343	
26	No. 75			780	
27	No. 124		4,344	5,836	1,492
28	No. 212		707	874	167

Notes: Δ – difference between 2023 and 2022

Source: compiled by the authors

The comparison of mineralisation and salt composition indicators between 2023 and 2022 shows significant fluctuations in concentrations for almost all indicators in well groups 9, 10, 11, 8 (tailings pond impact zone), 16, 19 (salt heap impact zone), and 13 (accumulating reservoir impact zone). In these cases, concentration changes of greater than or equal to 1 MAC fraction are observed. This phenomenon is logically explained by the proximity of the mentioned wells to the corresponding pollution sources of the aquifer. A significant reduction in overall mineralisation between 2022 and 2023 is observed in samples taken from the Dombrovskiy Quarry, wells 8, 10, and 16. A notable increase in overall mineralisation is observed primarily in well 9 (by 41.7 g/l), as well as in wells 11, 13, and 124. High mineralisation (over 29 g/l) was recorded in well

65, which was added to the monitoring network this year. This well is part of the monitoring network of the State Enterprise Potash Plant. For this well, MAC is also exceeded for all other components of the salt composition. The well requires special attention, as it is located to the south of the research area, between the Dombrovskiy Quarry and the Limnytsia River. Well No. 16, located 160 m north of No. 65, shows significantly lower mineralisation, about 1.7 g/l, and a negative concentration trend. This well is part of the new monitoring network installed by Noosphere. However, the samples taken from well 16 also exceed the MAC, though not by tens of times, as is the case for well No. 65.

The analysis of the dynamics of biogenic elements – ammonium ions, nitrites, nitrates, and orthophosphates – shows significant increases in concentrations, particularly

in well No. 9, especially for ammonium and nitrate ions. An increase in ammonium ion concentration is also observed in well No. 13. Negative changes in concentrations between 2023 and 2022 are recorded in wells 10, 8 (tailings pond influence zone), 16 (salt heap influence zone), 124, as well as samples from the Dombrovskiy Quarry and drainage trench.

For toxicological indicators, a comparison of iron and manganese concentrations was made. In 2023, manganese concentrations exceeded the MAC in wells No. 11, 13, 15, 24, 61, 65 (significantly, by 200 times), 74, 75, 124, 212. However, in 2022, most wells showed a decrease in concentration, except for wells No. 13 and 15. The highest iron content in 2023 was observed in well No. 65, exceeding the standard by 216 times. High iron levels were also recorded in wells No. 11, 9, and 61. The year-on-year dynamics revealed a significant increase in iron content in samples from wells No. 11, 10, 4, and 16. Most of the samples taken showed iron concentrations exceeding the MAC, except for those from the Dombrovskiy Quarry, drainage trench, and well No. 15.

Assessing the condition of groundwater and surface water in the areas of active or depleted mineral deposits is a crucial component of monitoring research. Hydrogeochemical studies are especially important because dangerous anthropogenic objects in the Kalush mining-industrial region (tailings ponds, salt heaps, sludge collectors, Dombrovskiy Quarry) are sources of pollutants for the region's surface and groundwater. The use of GIS tools for modelling processes and assessing the geological environment provides undeniable advantages. In the work by L. Davybidia & M. Tymkiv (2020), GIS were used to evaluate the state of the hydrogeological observation well network and to assess the optimal placement of monitoring wells. GIS cartography allows for the rapid generation of spatial distribution maps based on attribute tables. In this study, these maps represent the concentrations of pollutants obtained from the analysis of samples taken from observation wells. The presence of well coordinates allows for geocoding the tables with analysis results and generating the corresponding cartographic layer with attributes in a GIS environment.

O. Koshliakov *et al.* (2020) and O. Dyniak *et al.* (2023) confirmed that methods of hydrogeological and GIS modelling, based on monitoring hydrogeochemical studies, are essential as they help more accurately predict the dynamics of mineralisation and pollution, while considering all key influencing factors. They utilised spatial analysis and GIS modelling with the ArcMap toolkit, specifically the Darcy flow module, for modelling using the water balance method in the hydrogeological monitoring system for groundwater deposits. In particular, when interpolating data on the groundwater hydrostatic level in wells, the IDW method was used, which assumes that the influence of known data points decreases with increasing distance from the measurement location.

The researcher K.I. Sokolchuk (2022) also highlighted the suitability of using this method in interpolating hydrological data, comparing his results with those obtained using triangulation, spline interpolation, and Kriging. The IDW interpolation method was also applied in the current study to interpolate data from well analysis results and construct corresponding maps. As a result, maps were created that marked the research results from 2022 and 2023 (Fig. 2-4). A detailed analysis of specific indicators, based on their visual spatial distribution in the study area, can be made from the maps. All the maps share the common feature that the primary sources of increased pollutant values are tailings ponds, dumps of quarry No. 1 and No. 4, as well as areas of subsidence mounds.

Figure 2 presents the results of the analysis for total mineralisation (g/dm^3). As seen in the figure, elevated mineralisation (greater than 1 g/dm^3) is observed in the central and western parts of the study area in both 2022 and 2023. In 2022, the highest mineralisation values (over 18 g/dm^3) were observed in well No. 9, located southeast of the tailings pond. In 2023, the mineralisation significantly increased (by more than 3 times) to nearly 60 g/dm^3 . A significant increase in mineralisation is also observed in wells No. 11, 13, and 124 (listed from north to south), which are located in the western part of the site. At the quarry, mineralisation decreased by 5.2 g/dm^3 . For well No. 16, located south of the quarry, where an increase in mineralisation was observed in 2022 compared to 2021, a significant decrease of 6.7 g/dm^3 is now noted. The increase in mineralisation in wells No. 11, 13, and 124 should be associated with the influence of the tailings pond, resulting from the leaching of salts due to atmospheric precipitation. A large halo of salinisation located to the south of the quarry deserves special attention. It is associated with well No. 65, which belongs to the observation well network of the Potash Plant and from which samples were taken for the first time this year. No such high mineralisation values were recorded in nearby wells. Since a high mineralisation value is observed at point No. 65, the mineralisation isolines on the map are "artificially" interpolated, and consequently, the boundaries of the salinisation halo are not accurate. Repeated samples taken under monitoring conditions from well No. 65 and others added to the observation network this year will allow for more reliable conclusions regarding the mineralisation level of the aquifer.

Changes in the concentration of salts were also studied. Figure 3 shows cartograms of chloride concentration changes across the area. The results are similar to those observed for total mineralisation. Significantly higher values are observed in wells No. 65, 9, 10, 11, 16, 13, and 124. In the eastern, southeast, and northeast parts of the study area, no elevated chloride concentrations were recorded – values were less than 350 mg/dm^3 , except for well No. 5 in 2022, where elevated chloride levels can be attributed to the formation of a subsidence sinkhole.

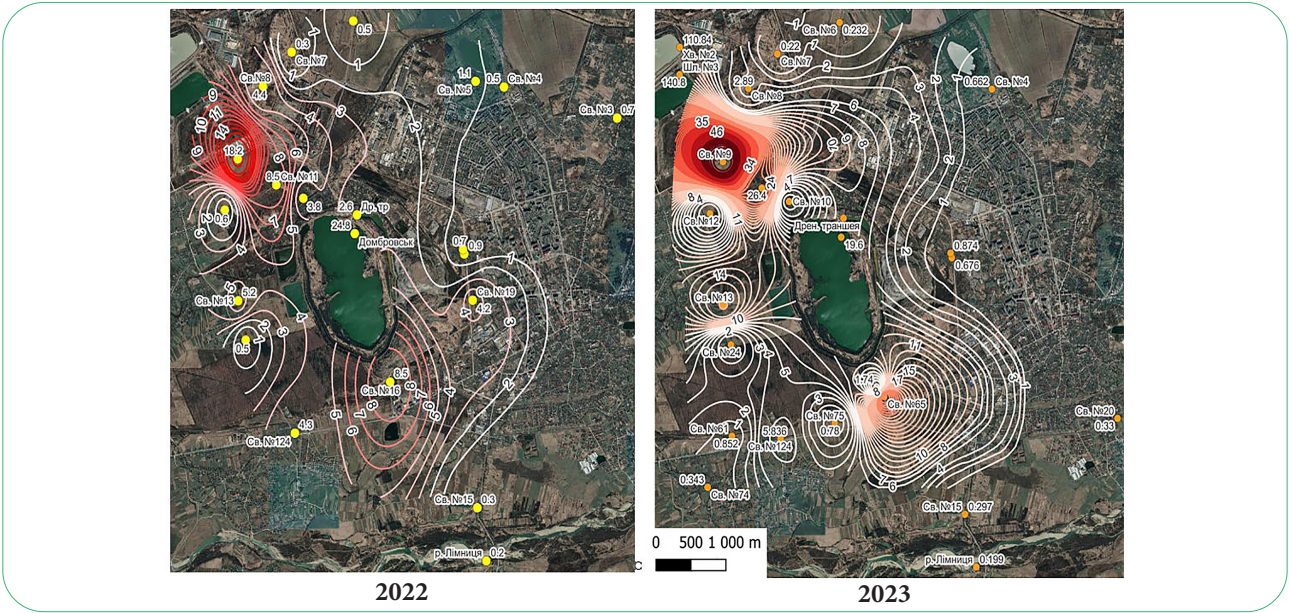


Figure 2. Cartograms of aquifer mineralisation, g/dm^3 , 2022-2023

Source: developed by the authors

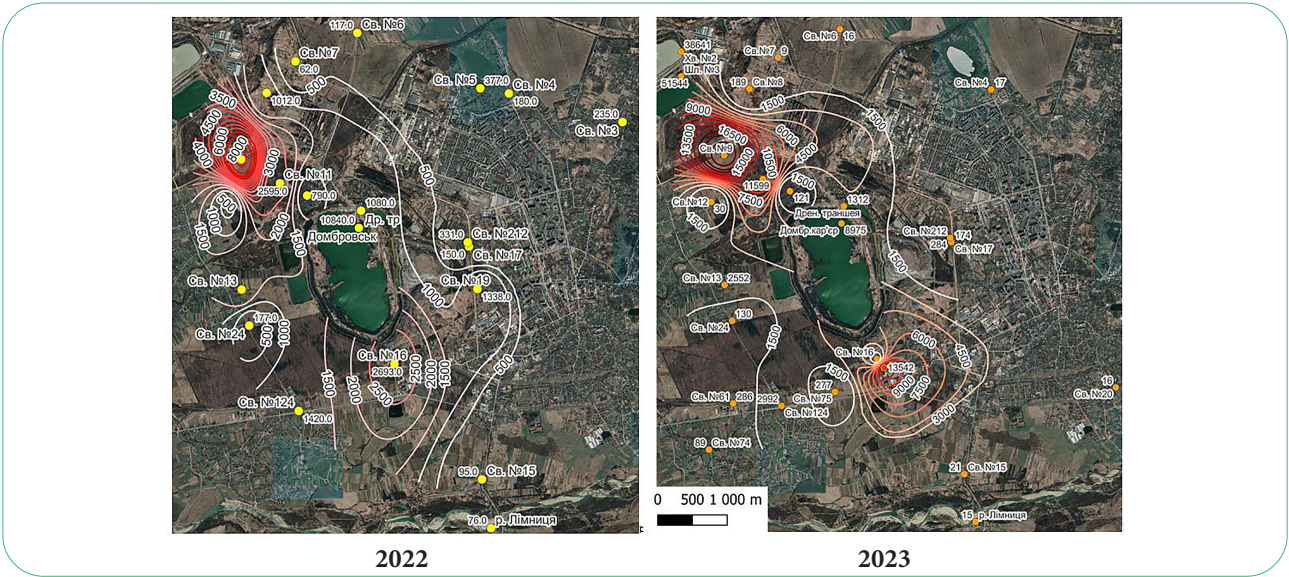


Figure 3. Cartograms of changes in chloride concentrations in the aquifer, mg/dm^3 , 2022-2023

Source: developed by the authors

The analysis of sulfate mass concentration changes shows that in 2022, the maximum permissible concentration (500 mg/dm^3) was exceeded in wells located to the northwest of the Dombrovskiy Quarry (wells No. 8, 9, 10, 11 – tailings pond impact zone) and to the southwest (wells No. 16, 19 – salt dump impact zone). In 2023, sulfate concentrations in wells No. 8, 9, 10, 11 (tailings pond impact zone) and well No. 16 (salt dump impact zone) decreased. Notably, well No. 65 showed significantly high sulfate concentrations. The analysis of calcium concentration dynamics revealed two distinct anomalous zones of elevated

calcium concentrations in the aquifer in 2022 and 2023: one to the northwest of the Dombrovskiy Quarry and another to the southeast. A decrease in calcium concentration by more than $1,200 \text{ mg/dm}^3$ was observed in the sample from the Dombrovskiy Quarry.

Figure 4 shows the distribution of magnesium concentrations based on the analysis conducted in 2022 and 2023. In 2022, magnesium concentrations exceeded the MAC in wells No. 9, 10, 11 (tailings pond impact zone), well No. 13 (tailings pond and accumulation facilities impact zone), and wells No. 16, 19 (salt dump impact zone). In the quarry

sample, magnesium concentration decreased from 1,477 to 379 mg/dm³ in 2022 compared to 2021, but in 2023, it increased to 679 mg/dm³ compared to 2022. In 2023, a clear expansion of the zone of elevated calcium concentrations was observed in the northeastern part of the area (near well No. 9), and likely an “artificial” extension of this

zone to the south of the quarry due to well No. 65, where a single measurement in 2023 showed significantly elevated magnesium concentrations. In the planar representation of salinisation dynamics for the periods 2021-2022 and 2022-2023, the maps of mineralisation differences are presented (Fig. 5).

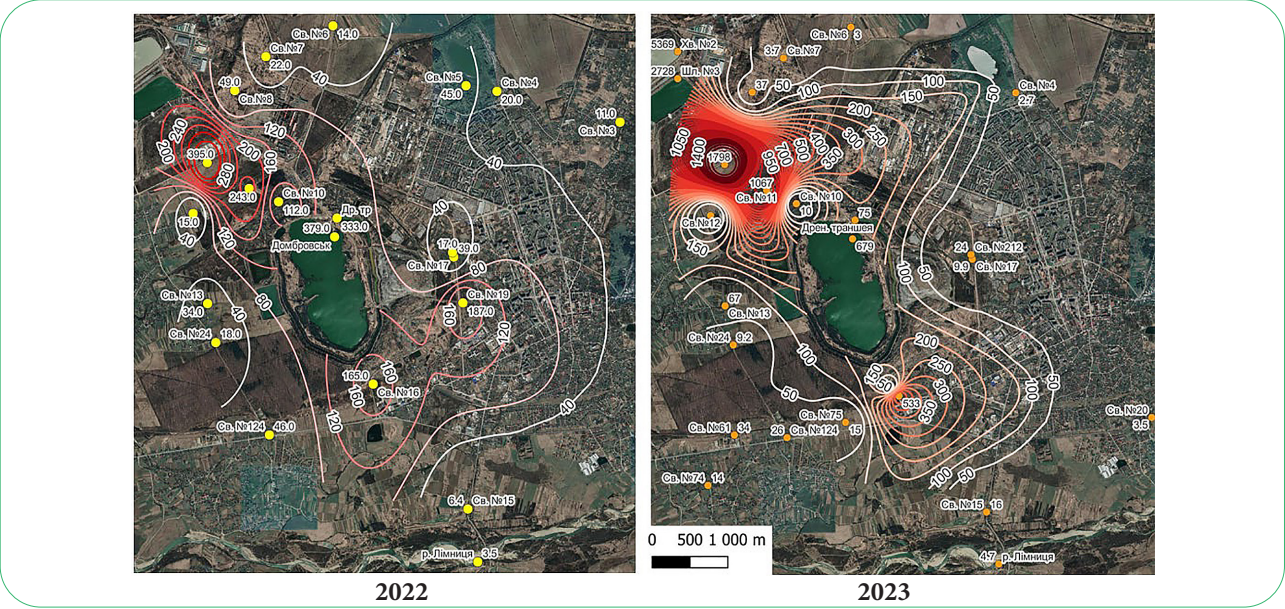


Figure 4. Cartograms of changes in magnesium concentrations in the aquifer, mg/dm³, 2022-2023
Source: developed by the authors

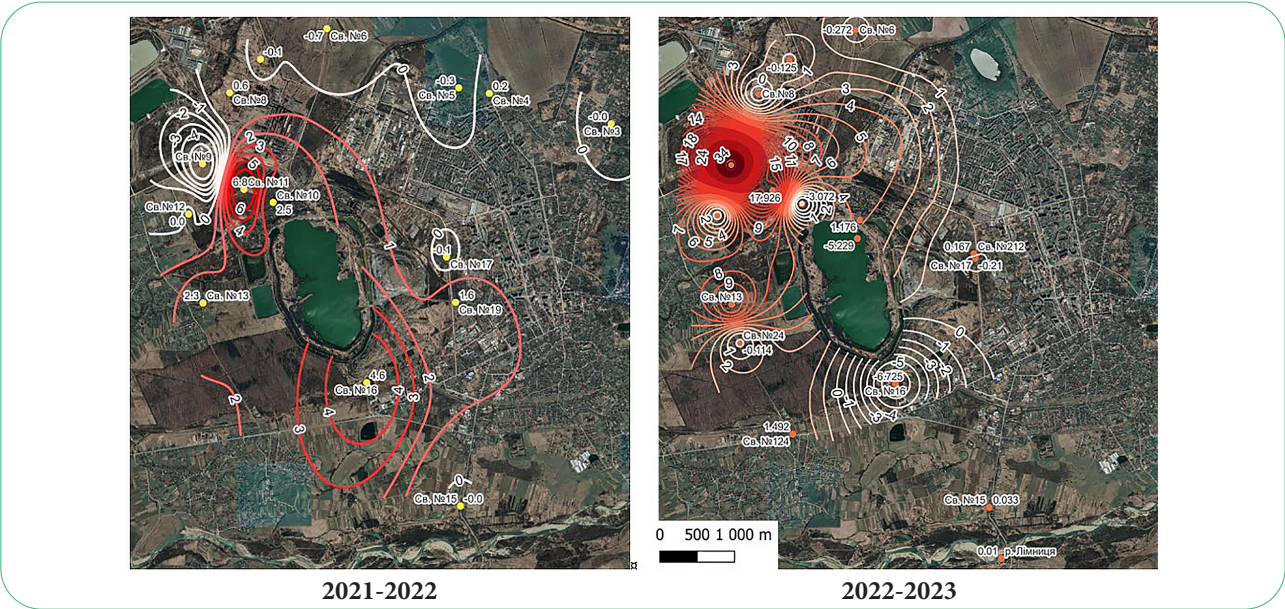


Figure 5. Cartograms with dynamics of groundwater salinisation
Source: developed by the authors

The dynamics of mineralisation for monitoring objects can also be traced through the graphs shown in Figure 6. In the figure, the vertical scale of concentrations is

presented in a logarithmic form, as there is a significant gap between the minimum and maximum values of mineralisation.

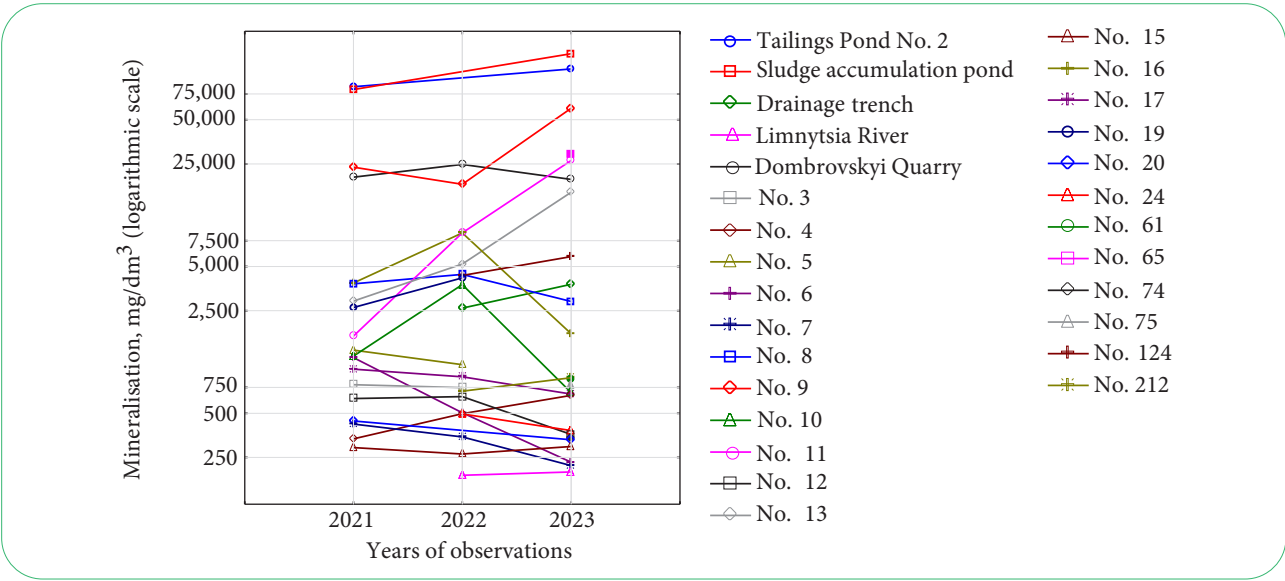


Figure 6. Graph of mineralisation dynamics for monitoring objects

Source: developed by the authors

In 2021-2022, the largest increases in mineralisation were observed in wells No. 11, 10 – the tailings pond zone, No. 13 – the tailings pond and accumulation facilities zone, No. 16, 19 – the salt dump zone. A significant decrease in mineralisation of more than 5 g/dm³ occurred in well No. 9. At the Dombrovskiy Quarry, during 2021-2022, an increase of 4.509 g/dm³ was observed, but in 2022-2023, a decrease of 5.229 g/dm³ was recorded. In 2022-2023, there was a significant increase in salinisation near well No. 9, with an increase of over 40 g/dm³, somewhat lower increases were observed in wells No. 13 and No. 124. A decrease in mineralisation was observed south of the quarry in well No. 16.

Analysis of Figures 5-6 suggests that, over the last year of observation, mineralisation has changed in a group of wells that are in the zone of direct influence of technogenic hazardous objects. The trend towards increased salinisation persists in wells No. 4, 9, 11, 13, 15, 124, 212, tailings pond No. 2, sludge collector No. 3, and drainage trench. The trend towards reduced salinisation is observed in wells No. 6, 7, 8, 12, 17, 20, and 24. Based on the analysis of the dynamics of mineralisation over the years, some trends can be traced (Fig. 2; Fig. 5-6). For example, a significant increase in mineralisation in 2023 compared to 2022 in the central and western parts of the study area, especially in well No. 9, where mineralisation increased by more than three times. In wells No. 13 and 124, located in the western part of the study area, an increase in mineralisation was also recorded, which is related to the influence of the tailings pond. The salinisation halo located south of the quarry was identified in well No. 65 (Fig. 2), where high levels of mineralisation were recorded. Chloride and sulfate levels vary across the study area and correlate with mineralisation, with increased levels noted in wells near

tailings ponds and quarries. This analysis demonstrates that the main areas of technogenic influence remain the zones near tailings ponds and quarries, where pollutant accumulation occurs in groundwater.

Changes in mineralisation in wells depend on a number of key factors, among which the determining factor for the conditions of the Kalush-Holyn mining and industrial region during the post-mining period is technogenic impact – namely the presence of tailings ponds, salt dumps, and the Dombrovskiy Quarry, as well as subsidence sinks. Erosion and leaching of salts from salt dumps and tailings ponds under the influence of atmospheric water are some of the primary sources of salinisation in groundwater. Leaching of salts and other chemical elements due to precipitation leads to increased mineralisation in adjacent wells. The danger posed by tailings ponds to the geological environment of surrounding areas is highlighted by V. Snitynskyi *et al.* (2021) and Z. Hevpa *et al.* (2023), with particular emphasis on the stability of the embankments of tailings ponds and the importance of continuous monitoring of the pulp levels and composition. Precipitation accelerates the process of leaching salts from technogenic dumps and tailings ponds, contributing to groundwater pollution. The increase in mineralisation may be associated with intense precipitation that leads to the active leaching of salts into the aquifer. As a result, spatial dynamics of salinisation halos can be observed in the studied area. The climatic factor also plays a significant role in increasing the water level of the Dombrovskiy Quarry, which may eventually lead to the penetration of brines into the Quaternary aquifer.

In the study by N. Sosonna *et al.* (2023), the possibility of brine leakage from the Dombrovskiy Quarry into the gravel and pebble aquifer is noted. The results of modelling showed that, after 40 years, the area of salinisation in

the aquifer under the influence of the Dombrovskiy Quarry will expand to 600 m. However, the leakage of brine from the Dombrovskiy Quarry is not expected to have a negative impact on the contamination of groundwater in the area of the Dobrovliany water intake, which is located to the south of the study area. Scenarios of flooding industrial salt extraction areas and their cross-border implications are presented in the work of S. Stadnichenko *et al.* (2023), where satellite imagery data were used to identify potential flooding zones during abnormal precipitation, and an assessment of water mineralisation in the flood risk areas was based on monitoring well data for the Quaternary aquifer. This highlights the need for constant hydrogeochemical monitoring of the observation well network. The necessity of organising comprehensive monitoring of the underground hydrosphere is also emphasised by B. Stetsenko *et al.* (2021), citing the example of the Solotvyn Salt Deposit.

Scientists S. Dovhyi *et al.* (2019), G.I. Rudko & E.O. Yakovlev (2020), and S.B. Shekhunova *et al.* (2021) highlighted that effective management of environmental problems at potash salt deposits requires investment in modern technologies, land reclamation, and continuous monitoring of the environment. This requires a scientific and production complex for post-mining activities based on scientific and technical measures aimed at preventing hazardous changes in the geological environment. A significant number of publications testify to the considerable negative impact of technogenic objects formed as a result of mining activities at potash salt deposits on the development of pollution and salinisation of groundwater. The study by Y.O. Malkova *et al.* (2023) also noted the impact of the Kalush-Holyn Potash Deposit's salt dumps on the chemical composition of groundwater. Through statistical processing of geochemical data, the levels of impact from potential sources of chemical contamination of groundwater (water from the Dombrovskiy Quarry, tailings ponds, sludge ponds, salt dumps, and saline soils) were analysed, as well as the correlation between heavy isotopes of hydrogen and oxygen and groundwater mineralisation.

The quantitative and qualitative values of the physicochemical and chemical indicators in the wells observed from 2021 to 2023 did not allow for a clear classification of wells by the probable technogenic source of contamination. On the maps, spatial dynamics of salinisation halos can be observed. Continuing monitoring observations will allow for the accumulation of time series data for each well, opening up the possibility of time series analysis. Modelling changes in mineralisation based on time series will help to identify long-term trends and predict future changes using regression analysis methods, autocorrelation models, or machine learning. It will also be possible to establish dependencies on meteorological and climatic factors, which directly influence the dynamics of chemical and physicochemical indicators in monitoring wells.

It is important to note that to obtain more reliable results for determining contamination zones in the aquifer

based on various indicators, a denser network of observation wells and a uniform distribution across the area are required. It is also crucial to collect samples and conduct chemical analysis with less frequency, for example, quarterly, to obtain reliable data. For decision-making, an integrated management model for the Kalush-Holyn industrial area during the post-mining stage should be introduced. This model would include the management and search for optimal methods of monitoring studies and the development of a set of environmental protection measures to reduce the negative impact of technogenic factors.

✓ Conclusions

Technogenic hazardous objects, created as a result of their operation, can be a source of significant water pollution. The Kalush mining and industrial district, with numerous objects such as the Dombrovskiy Quarry, sludge reservoirs, and tailings ponds, is one of the regions experiencing considerable technogenic pressure. Water samples have recorded exceedances of the MAC of chlorides and sulfates. In particular, at sludge reservoir No. 3, tailings pond No. 2, and the Dombrovskiy Quarry, the concentration of chlorides exceeds the norm by 25-147 times, and sulfates by 3-42 times. This indicates a critical level of salinity in the waters, which may negatively affect ecosystems and drinking water sources. Quaternary aquifers, which are used for public water supply, are experiencing significant technogenic impact. High mineralisation and exceedance of MAC for chlorides, sulfates, calcium, and magnesium in the wells suggest a gradual deterioration in the quality of groundwater in the area influenced by tailings ponds, sludge reservoirs, and the Dombrovskiy Quarry.

Comparison of data from 2022 and 2023 revealed significant fluctuations in pollutant concentrations in wells located in the zones of technogenic object influence. A considerable increase in concentrations was recorded in a number of wells, indicating the continued negative impact of technogenic sources on the aquifers. Despite the negative impact of technogenic objects on groundwater, the water quality of the Limnytsia River remains stable, with only minor deviations from regulatory values for mineralisation and chemical composition. It is necessary to strengthen monitoring and protection measures for the region's water resources. It is recommended to continue systematic sampling from wells, especially those located near sources of technogenic pollution. Regarding future research, measures for the reclamation of technogenic objects should be developed to reduce their impact on groundwater, along with additional studies to determine the possibilities for cleaning or minimising pollution in the water horizons.

✓ Acknowledgements

None.

✓ Conflict of Interest

None.

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Моніторингові дослідження еколого-гідрогеохімічної ситуації у зоні впливу техногенних об'єктів гірничопромислового комплексу Калуш-Голинського родовища калійної солі

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✓ **Анотація.** Оцінка стану підземних і поверхневих вод на територіях відпрацьованих соляних родовищ корисних копалин є важливою складовою моніторингових досліджень через значний техногенний вплив таких об'єктів, як хвостосховища, шламонакопичувачі та Домбровський кар'єр. Метою дослідження було встановлення на основі реальних експериментальних даних гідрогеохімічних аналізів багаторічного моніторингу підземних вод за мережею спостережних гідрогеологічних моніторингових свердловин площ засолення підземних вод Калуського гірничопромислового району, оцінка динаміки хімічних та фізико-хімічних показників і загроз для екологічної ситуації району. Етапи досліджень передбачали систематизацію моніторингових даних за 2021-2023 роки, створення цифрових картографічних шарів та атрибутивних баз даних із даними щодо кількісних показників хімічного складу підземних вод, геоінформаційне моделювання та побудову карт засолення території Калуського гірничопромислового району та динаміки засолення водоносного горизонту. У 2023 році на території Калуського гірничо-промислового району було проведено гідрогеохімічні дослідження з відбором 25 проб зі спостережних свердловин, Домбровського кар'єру, шламонакопичувачів та річки Лімниця. Проаналізовано мінералізацію та хімічний склад води. Результати досліджень показали, що найбільший рівень мінералізації спостерігався у водах шламонакопичувача № 3 та хвостосховища № 2, де рівні мінералізації перевищували гранично допустимі концентрації в 140 та 110 разів відповідно. Вміст хлоридів і сульфатів у цих об'єктах також значно перевищував допустимі норми. Порівняння даних за 2022 та 2023 роки показало значне зростання концентрацій забруднюючих речовин у низці свердловин, що підтверджує продовження негативного впливу техногенних об'єктів. Водночас якість води в річці Лімниця залишилася стабільною. Цінність роботи полягає в оцінці екологічного стану підземних вод Калуського гірничо-промислового району на основі систематизації даних гідрогеохімічного моніторингу за мережею спостережних свердловин із використанням геоінформаційних підходів моделювання

✓ **Ключові слова:** відпрацьовані соляні родовища; спостережні свердловини; підземні води; геоінформаційна система; моделювання



Evaluation of ground-based methods for monitoring neotectonic processes at geodynamic sites

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✓ **Abstract.** The relevance of the article lies in the need to improve the methods of monitoring neotectonic processes and develop technological parameters to ensure more effective forecasting of geodynamic phenomena. Accurate monitoring of neotectonic processes is important for assessing changes in geological conditions and preventing potential risks affecting the environment and human life safety. The purpose of research was to evaluate the effectiveness of various ground-based methods of monitoring neotectonic processes to determine their reliability and accuracy. The authors used different methods, in particular geodetic measurements, which ensure high accuracy and reliability of the results; geophysical methods that help to detect subsurface structures and processes; and remote sensing of the Earth, which provides large-scale monitoring and analysis of the dynamics of neotectonic phenomena. Having analysed the existing methods of determining the changes in the shape of the equipotential surface, the advantages of using geodetic measurements to ensure the accuracy and reliability of the measurement results were identified and substantiated. The proposed methodology is based on the study of changes in the shape of the equipotential surface on geotechnological sites and takes into account the inhomogeneity of the gravity field, and if the developed technological parameters are followed, it ensures the determination of the deflection of plumb lines with an accuracy of $\pm 0.2''$. The research results showed that the combination of these methods helps to obtain a more complex picture of neotectonic processes, which, in turn, contributes to more accurate forecasting and prevention of the consequences of geodynamic phenomena. The proposed approach to monitoring neotectonic processes can be used to develop effective strategies for monitoring and managing environmental risks associated with geological hazards

✓ **Keywords:** hypsometric elevations; orthometric correction; geoid; deflection of the plumb line from the normal; geometric levelling; GNSS observation

✓ Introduction

Earthquakes and other unfavourable underground physical and geographical processes, such as erosion, landslides, mudslides, karst, continue to pose a significant threat to human life and cause risks to the safe operation of buildings and structures on the Earth's surface. The main approaches

and methods for solving the problem of monitoring neotectonic processes include the use of satellite data, geodetic measurements and numerical modelling. The disadvantages of existing approaches include high cost, complexity of integration of different data types, and insufficient accuracy

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in short-term forecasting. This indicates the need to develop new methods that take into account these limitations and provide more accurate and operational monitoring. Research and development in this direction will contribute to minimising the destructive impact of earthquakes and adverse physical-geographical processes on society, as well as deepen the existing understanding of the structure and dynamics of the Earth's surface movement.

According to D.R. Raban & A. Gordon (2020), the rapid progress of information technology has contributed to the exponential growth of big data volumes, including spatial data. Researchers M. Shafapourtehrany *et al.* (2023) also noted the development of forecasting and simulation modelling techniques, but short-term earthquake forecasting remains a challenging and unsolved problem. According to M. Pakshyn *et al.* (2019), satellite technologies such as synthetic aperture interferometry allow obtaining high-precision data on changes in the Earth's surface. However, these methods have their limitations in the form of high cost and the need for specialised equipment. Among the available technologies for earthquake research, remote sensing is widely used due to its unique characteristics such as rapid image acquisition and wide image acquisition range. However, early studies of pre-earthquake anomalies and remote sensing are mostly focused on anomaly identification and analysis of a single physical parameter. The combination by researchers P. Xiong *et al.* (2021) of infrared and hyperspectral studies of the terrain over a significant period of time is quite voluminous, and cannot do without the participation of machine learning methods, the results of which demonstrate a strong ability to improve earthquake forecasting.

X. Zhao *et al.* (2021) tentatively distinguished four application areas of remote sensing data for earthquake prediction based on observed anomalies: thermal anomalies, electromagnetic signal anomalies, crustal deformations, and gravity anomalies. C. Geiß *et al.* (2020) noted that geodetic methods, particularly ground-based global navigation satellite systems (GNSS), are effective for monitoring deformation, but their accuracy depends on the density of the observing stations network. C. Chen *et al.* (2020) considered it possible to track surface displacements with GNSS data that exhibit elastic deformation and/or oscillations in the spatiotemporal domain, if double-amplitude vibrations actually exist. Vertical displacements obtained from ground-based GNSS receivers can be taken into account to test the effects of double-amplitude vibrations in dynamic range seismic records at such low frequencies (i.e., a cycle of about 2 hours).

The main approaches and techniques used to monitor neotectonic processes include synthetic aperture radar (InSAR) interferometry, GNSS, and gravity variation analysis. According to J.B. Rundle *et al.* (2021), InSAR allows obtaining high-precision images of deformations of the Earth's surface. However, according to researchers S. Nandan *et al.* (2021), this method has limitations in densely built-up or forested areas due to the possibility of signal loss. M. Bagheri-Gavkosh *et al.* (2021) emphasised the

importance of integrating different methods to ensure a comprehensive approach to monitoring. The researchers highlighted the importance of monitoring changes and deformations of the Earth's surface to understand the impact of anthropogenic activities, which currently pose major challenges to the global community. O. Lavryk (2018) stated that the monitoring of landscapes and technical systems is part of interdisciplinary geotechnical monitoring, which is carried out for the comprehensive study of changes in the Earth's surface and their dynamics, as well as for the study of factors affecting displacement.

Despite significant progress in monitoring technologies, existing approaches have limitations. Some techniques, such as InSAR, may be limited by terrain conditions. GNSS-based methods require significant financial and technical resources for installation and maintenance. Therefore, there is a need to develop new techniques that can provide accuracy and reliability at lower costs and less dependence on local conditions. The purpose of this work was to develop a methodology and substantiation of technological parameters to study changes in the shape of the equipotential surface on geotechnological sites. The scientific novelty of the research lies in the fact that new approaches to monitoring neotectonic processes have been developed, which take into account modern technological capabilities and ensure high accuracy and speed of data. The technological parameters used to study changes in the shape of the equipotential surface on geotechnological polygons have been investigated, which ensures the accuracy of determining the deflection of plumb lines of 0.2" and takes into account the inhomogeneity of the gravity field.

✓ Materials and Methods

Investigating the influence of the level surface shape on the results of geodetic levelling, P. Dvulit *et al.* (2012) stated that in mountainous areas, the mean square error of the deflection of the plumb line from the normal is 8", and the maximum value can reach 1". Regardless of the complexity of the topography and terrain anomalies, the deflection of vertical components can be calculated with an accuracy of more than 0.1" using the provided formulas. In (1), the accuracy of calculating the deflections of plumb lines from the normals expressed in terms of the root mean square error is calculated:

$$m_{\varepsilon} = \frac{\rho}{s \sin Z} \times m_h, \quad (1)$$

where m_{ε} is the accuracy of calculating deflections of plumb lines from normals; m_h is the root mean square error to determine elevations; S is the distance between site points; Z is zenith distance; ρ is a constant describing the number of seconds in one radian (206,265"). The mean square error of geometric levelling for Class I is calculated by the formula:

$$m_h^2 = \eta^2 \times S + \sigma^2 \times S^2, \quad (2)$$

where η is the random error of geometric levelling (0.8 mm is taken for Class I); σ is the systematic error of geometric levelling (0.08 mm is taken for Class I) according

to (Perii, 2019); S is the distance between site points. The deflection of the plumb line from the normal is determined by comparing the zenith distances obtained with the help of GNSS levelling Z^{GNSS} (determined in relation to the ellipsoid) and geometric levelling Z^{ort} (determined in relation to the geoid):

$$\varepsilon = Z^{\text{GNSS}} - Z^{\text{ort}}, \quad (3)$$

where ε is the deflection of the plumb line from the normal. Figure 1 shows a section along a vertical plane between two points of a geodynamic site with a given azimuth – α_{AB} . Thus, in Figure 1, plumb lines and the normal are represented as projections on a vertical section, which is a plane of a direct normal section. This section includes the normals to the ellipsoid at points A and B , as well as the projected normal that is goes down from point B to point A .

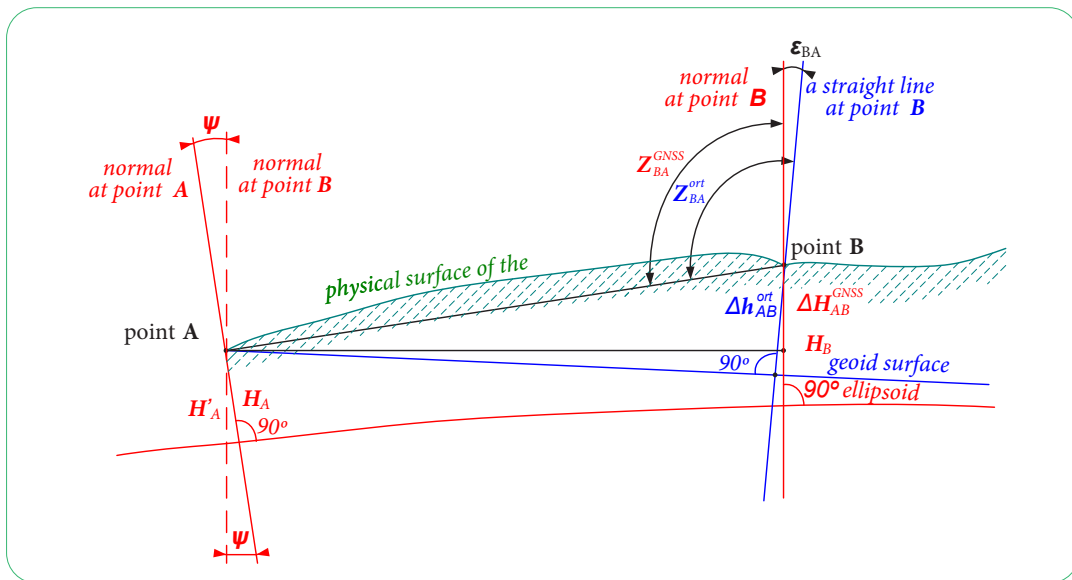


Figure 1. Vertical section along the line of the geodynamic site

Source: created by the authors

To calculate the zenith distances of Z^{GNSS} and Z^{ort} , it is necessary to determine the height difference of two points relative to the surface of the geoid and the reference ellipsoid, and their geodetic coordinates (Lysko, 2023). Based on Figure 1, the following was obtained:

$$\begin{aligned} Z_{AB}^{GNSS} &= \arccos \frac{\Delta H_{AB}^{GNSS}}{S_{AB}}; \\ Z_{BA}^{GNSS} &= 180 - \arccos \frac{\Delta H_{BA}^{GNSS}}{S_{AB}}; \\ Z_{AB}^{ort} &= \arccos \frac{\Delta h_{AB}^{ort}}{S_{AB}}; \\ Z_{BA}^{ort} &= 180 - \arccos \frac{\Delta h_{BA}^{ort}}{S_{AB}}, \end{aligned} \quad (4)$$

where ΔH_{AB}^{GNSS} is the difference in geodesic heights with account of the normal projection; Δh_{AB}^{ort} – is the difference in hypsometric heights with account of the orthometric correction; S is the distance between polygon sites. As the normals at points B and A were not parallel to each other, a projection of the normal was made, which was taken from point B to point A . Thus, the following formula was used to determine the elevations by geodetic heights of the points:

$$H_{AB}^{GNSS} = H_B - \frac{H_A}{\sin \psi}, \quad (5)$$

where ΔH_{AB}^{GNSS} is the difference in geodesic heights with account of the normal projection, taken from point B to

point A ; ψ is a dihedral angle formed by two normal, which is calculated according to the formula from analytical geometry, as an angle between two vectors. Hypsometric elevations dh^{ort} describe the physical surface of the Earth relative to the horizontal. This is the more difficult part to determine compared to geodesic elevations. Hypsometric elevations were obtained according to the formula:

$$\Delta h_{AB}^{ort} = [h]_{AB} + O_{AB}^{ort}, \quad (6)$$

where $[h]_{OP}$ is the sum of elevations between observation stations O and P , obtained from geometric levelling data and corrected by orthometric p^{ort} correction. In the S. Perii (2019) study, to determine the zenith distances Z^{GNSS} and Z^{ort} the equations of the normals are solved, which go down from the observation stations A and B . Given the parameters of the ellipsoid (WGS84), the coordinates of the intersection of the normals with the Z axis at the points nA and nB were found. The coordinates of the intersection points of the normals with the Z axis were determined by calculating the distances $0nA$ and $0nB$ from the origin of the coordinates to the intersection points. Since the coordinates of the observation points are obtained from GNSS measurements, the coordinates of the intersection points with the Z axis are obtained by formulas using the parameters of the reference ellipsoid (Zakatov, 1962).

$$\left. \begin{aligned} X_{nA} &= Y_{nA} = 0 \\ Z_{nA} &= -\frac{ae^2 \sin B_A}{\sqrt{1-e^2 \sin^2 B_A}} \end{aligned} \right\}; \quad \left. \begin{aligned} X_{nB} &= Y_{nB} = 0 \\ Z_{nB} &= -\frac{ae^2 \sin B_B}{\sqrt{1-e^2 \sin^2 B_B}} \end{aligned} \right\}, \quad (7)$$

where $e \rightarrow a$ are the geometric parameters of the referent ellipsoid; B is the geodetic latitude of the point. The coordinates of points nA and nB on the Z axis acquired the values

$(0, 0, Z_A)$, $(0, 0, Z_B)$, respectively. Zenith distances are calculated as the angle between two vectors using the geocentric coordinates of points:

$$\begin{aligned} Z_{AB}^{GNSS} &= \arccos\left(\frac{X_A(X_B-X_A)+Y_A(Y_B-Y_A)+(Z_A-Z_{nA})(Z_B-Z_A)}{\sqrt{X_A^2+Y_A^2+(Z_A-Z_{nA})^2} \times \sqrt{(X_B-X_A)^2+(Y_B-Y_A)^2+(Z_B-Z_A)^2}}\right); \\ Z_{BA}^{GNSS} &= \arccos\left(\frac{X_B(X_A-X_B)+Y_B(Y_A-Y_B)+(Z_B-Z_{nB})(Z_A-Z_B)}{\sqrt{X_B^2+Y_B^2+(Z_B-Z_{nB})^2} \times \sqrt{(X_A-X_B)^2+(Y_A-Y_B)^2+(Z_A-Z_B)^2}}\right). \end{aligned} \quad (8)$$

Although these methods are conceptually different, they rely on the results of geometric levelling together with data on the vertical gradient of gravity to determine the hypsometric component dh^{ort} (orthometric height of a physical point on the Earth above the geoid) and high-precision GNSS measurements. To ensure the maximum level of accuracy and reliability of the obtained results, when developing an alternative method of determining deflections of plumb lines, the following condition should be observed: heights have to be determined unambiguously, regardless of the levelling method. To strictly comply with this requirement, it is necessary to use the geopotential value $C = \int_0^p g dh$. This integral does not depend on the form or path of integration, that is, integration along different levelling courses should give the same result; the heights should be determined based only on the results of direct measurements on the physical surface of the Earth, without using hypothetical data about its internal structure. Hypothetical data are subject to interpretation and internal assumptions, which may adversely affect the objectivity of the results; the accepted system of heights should correspond to a rather strict method of determining the geoidal component of a geometric or geodetic height. The optimal solution for height provision of a geodynamic site is using the orthometric system of heights and developing a direct connection with geodetic heights. This possibility is provided by Helmert's differential formula for determining the elevations of the geoid:

$$d\zeta = \zeta_0 - \zeta_p = -\int_A^B \varepsilon^e dl - \int_A^B \frac{g-\gamma}{\gamma} dh, \quad (9)$$

where ε^e is the mean value of the plumb line deflections determined on the physical surface of the Earth; l is the distance between observation stations. Since the geoid is a level surface and any hypsometric elevations of dh on this surface will be zero, then equation (9) has taken the following form:

$$d\zeta = \zeta_0 - \zeta_p = -\int_A^B \varepsilon^e dl. \quad (10)$$

Based on equation (10), the deflection of the plumb line was expressed in the following way:

$$\varepsilon^e = \frac{d\zeta}{dl}. \quad (11)$$

The heights difference of the geoid $d\zeta$ cannot be obtained from the results of direct measurements on the physical surface of the Earth, and the use of hypothetical

data about its internal structure is subject to interpretation and internal assumptions. It is appropriate to express the difference in geoid heights $d\zeta$ through geodesic ΔH_{Op}^{geod} and orthometric dh^{ort} heights. This possibility is directly provided by the integral formula of the generalised astronomical levelling. It is provided in the following interpretation:

$$d\zeta = \int_0^P dH^{geod} - \int_0^P dh^{ort}. \quad (12)$$

This approach made it possible to additionally control the results of measurements due to the comparison of geodetic elevations obtained directly from GNSS measurements and from the results of ground-based measurements, which provides a significant advantage of using the proposed technique in comparison with existing analogues.

Results

A number of various factors, such as tectonic activity, subsidence due to withdrawal of liquids from the subsurface, and volcanic activity, cause deformations of the Earth's surface. These processes lead to a redistribution of masses in the Earth's crust, a change in the gravitational potential, and therefore a change in the shape of the equipotential surface. Measuring the change in the shape of the equipotential surface helps to get an idea of the main geological processes and gravitational potentials. Observing the nature of these changes provides insight into the nature and degree of deformation of the Earth's surface and is the basis for short-term forecasting. Deformation, in the broadest sense, is a change in shape and dimensions. As the form and figure are related to the metric characteristics of bodies, deformation, in a broad sense, is also related to the change in such characteristics of general physical or even abstract entities. It is only necessary for the elements of such objects to be brought into correspondence with each other, just as through the identification of material points a correspondence is established between two different states of a deformable body. Studying the dimensions, shape and gravitational field of the Earth, determining the position, changes in time of all of the above mentioned, as well as their representation, play an important role in investigating the processes taking place on the planet (Dermanis & Livieratos, 2023). This issue is particularly relevant for environmental safety, since by monitoring neotectonic processes it is possible to predict their course for the timely warning of society in order to minimise probable destructive consequences.

Significant negative consequences of surface deformations have led to the existence of numerous methods of studying and monitoring deformations of the Earth's surface, which arise as a result of natural geodynamic processes, man-made and exogenous factors. The choice of measuring devices and methods or the creation of a special monitoring system depends on different types of deformations, which will affect the stability analysis method and, accordingly, the entire deformation monitoring system. The study of spatio-temporal deformation changes of technogenically destabilised territories includes a number of geodetic, geological, geophysical, geotechnical methods or their combinations. Geodetic methods can be divided into remote, terrestrial and terrestrial-remote based on the spatial location of research instruments at the time of shooting. The main directions of the development of modern geodesy are related to the development of information technologies, in particular,

GNSS, high-resolution orbital systems for creating surface deformation maps or a digital terrain model (Karpinsky & Lazorenko-Hevel, 2018).

The development of powerful means of obtaining spatial information about the Earth is based on a variety of technologies, including optical-electronic terrain scanning systems, satellite radar, laser location on ground and air platforms, digital aerial photography (including the use of unmanned aerial vehicles (UAV) and non-metric cameras), pictographic imaging to create realistic terrain models, digital methods of processing images and geospatial information, and extensive use of GIS and telecommunications technologies to provide public access to geospatial data. V. Hlotov & M. Biala (2023) proposed a detailed classification of current geodetic methods and techniques of researching quantitative parameters of deformation processes of subsidence-settlement of the Earth's surface of man-made destabilised territories (Fig. 2).

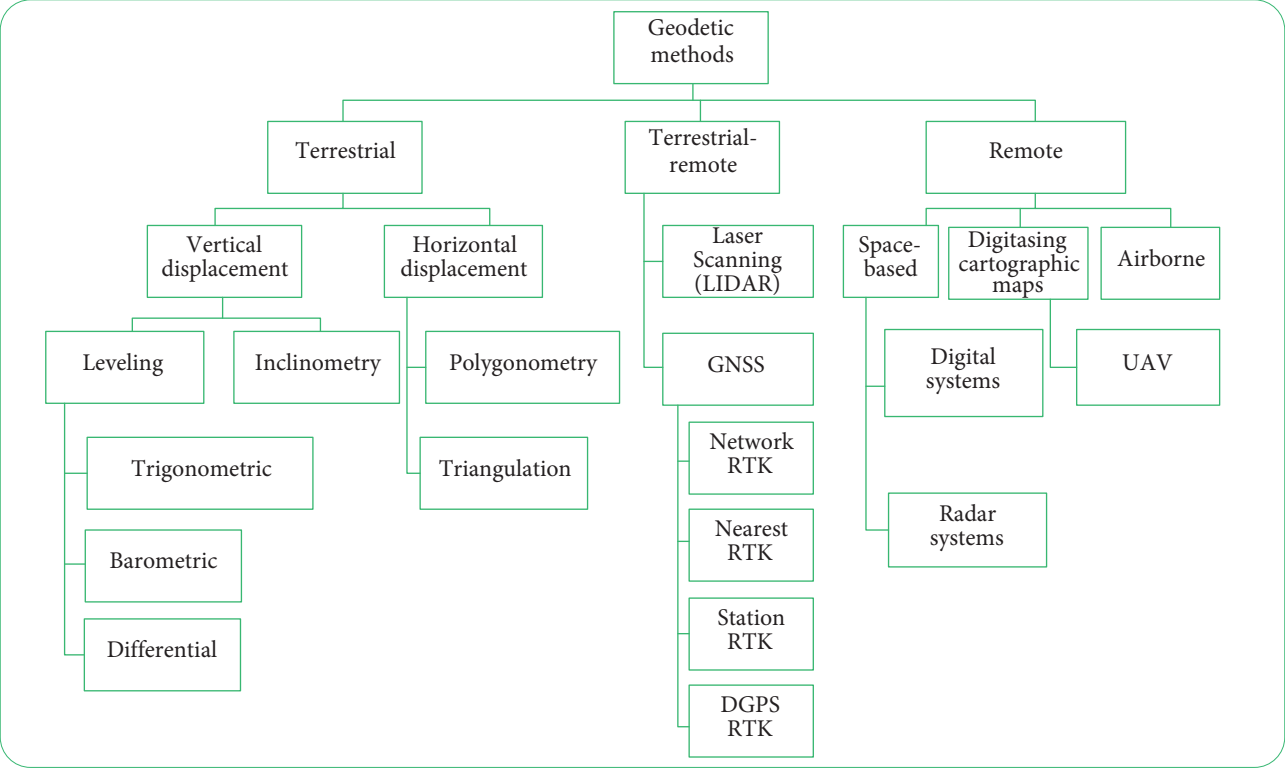


Figure 2. Classification of relevant geodetic methods for monitoring and studying deformation spatio-temporal changes of the Earth's surface in man-made destabilised territories
Note: RTK – real time kinematic; DGPS – differential global positioning system
Source: created by the authors based on V. Hlotov & M. Biala (2023)

The collected data are used to protect the natural environment through the identification and monitoring of areas with an increased risk of natural disasters, which allows timely preventive measures. To ensure environmental safety and the safety of human life in the studied territories, the data are used to predict and minimise risks associated with earthquakes and other adverse physical

and geographic processes. This facilitates the development of effective evacuation plans and emergency response measures. The rational use of natural resources is ensured through the assessment of their state and the dynamics of changes, which allows planning their sustainable use. In the programs of regional development of territories, the data helps to determine the safest and most stable areas for

construction and infrastructure development, taking into account possible geological threats (Zayats *et al.*, 2017).

Remote sensing methods based on the analysis of the Earth's gravity field are widely used to determine changes in the equipotential surface. These methods include satellite gravimetry, doppler interferometry, satellite altimetry and satellite laser ranging. Methods based on the use of InSAR deserve special attention among the above measurement methods. InSAR results are partially available for public use and have become widely used in scientific research. Their main advantage is the possibility of carrying out mapping and monitoring of the Earth's surface deformation on a continental scale (Kalia *et al.*, 2017; Raspini *et al.*, 2018). Data obtained from orbital satellites help to get global data about the Earth's gravitational field, which can potentially be used to monitor changes in the equipotential surface.

Methods that are carried out on the Earth's surface consist in measuring the deflection of a plumb line or the change in the strength of the Earth's gravitational field directly on the ground. They can provide higher accuracy compared to remote methods, optimal resolution, they have advantages in ease of maintenance and independence from weather conditions. Such advantages of terrestrial methods in determining changes in the equipotential surface make them more reliable and suitable for predicting deformations of the Earth's surface. These methods make it possible to detect local changes in the equipotential surface, which is an additional advantage in their application. Gravimeters are widely used to measure the strength of the gravitational field on the Earth's surface. Maps of the Earth's gravitational field can be developed based on the dynamics of changes in the gravitational field intensity over time. These maps are used to determine changes in the shape of the equipotential surface. These data allow for high accuracy and are used to monitor changes in the Earth's gravitational field, both local and regional (Burak, 2022).

When using ground-based gravity methods, there is no influence of atmospheric interference and positioning errors. However, the disadvantage of these measurements is the low efficiency, since one point can take several tens of hours to measure. Ground-based gravimetric measurements respond to local terrain characteristics because they are performed on the physical surface of the Earth, not on the geoid itself. If changes in the distribution of topographic masses occur above the geoid surface, this will not affect the geoid shape, as such masses are not taken into account when determining it. However, changes in mass distribution can still lead to deflections in the gravitational potential on the Earth's surface. Ground-based gravimetry methods, such as relative and absolute gravimetry, provide a direct measurement of the gravitational potential, making them particularly sensitive to changes in the mass distribution over the geoid surface. Nevertheless, they can be effective in detecting changes in

the geoid shape if combined with high-precision geodetic measurements.

P. Dvulit *et al.* (2019) singled out methods that are not affected by the change in mass distribution over the geoid surface as particularly promising for determining the deflection of plumb line. Such methods include astro-geodetic levelling, geometric levelling, and GNSS levelling, which focus on determining the direction or vector of gravity, instead of the absolute value of the gravitational potential (Ceylan, 2009). Changes in the direction of gravity help to make inferences about changes in mass distribution that affect the gravitational field, without the need to consider the absolute value of the gravitational potential. This approach was taken into account during the development of the proposed methodology, which made it possible to obtain a more comprehensive picture during the monitoring of neotectonic processes.

Based on the calculations, differential equations were obtained and the influence of technological parameters on the accuracy of determining the deflection of plumb lines from normals was investigated, depending on the chosen method. Geodetic and hypsometric elevations are considered to be uncorrelated, so the root mean square error of the function can be obtained by summing the squares of the partial derivatives calculated for each variable. When using the technique based on the comparison of zenith distances obtained with the help of hypsometric and geodetic heights (hereinafter Method I), the generalised differential equation look as follows:

$$\sigma_{\varepsilon}^2 = \left(\frac{1}{S_{AB}^2 - \Delta H_{AB}^2} \right) (\sigma_{\Delta H}^2 + \sigma_{\Delta h}^2) + 2 \left(\frac{\Delta H_{AB}^2}{S_{AB}^2 (S_{AB}^2 - \Delta H_{AB}^2)} \right) \sigma_{\Delta S}^2, \quad (13)$$

where $\sigma_{\Delta H}^2$ is the accuracy of determining the difference in geodetic heights; $\sigma_{\Delta h}^2$ is the accuracy of determining hypsometric elevations; $\sigma_{\Delta S}^2$ is the accuracy of determining the distance between observation stations; S is the distance between site points. The differential equation of the proposed method of determining deflections of plumb lines, based on Helmert formula for astronomical levelling (hereinafter Method II) look as follows:

$$\sigma_{\varepsilon}^2 = \frac{1}{S_{AB}^2} (\sigma_{\Delta H}^2 + \sigma_{\Delta h}^2) + \left(\frac{\Delta H_{AB}^{GNSS} - \Delta h_{AB}^{ort}}{S_{AB}^2} \right)^2 \sigma_{\Delta S}^2. \quad (14)$$

Based on the analysis of differential equations (13-14), it can be concluded that the obtained accuracy of determining the deflection of a plumb line from the normal (σ_{ε}^2) depends on the squares of the measurement errors of hypsometric $\sigma_{\Delta h}^2$ and geodetic elevations $\sigma_{\Delta H}^2$ in direct proportion, and is inversely proportional to the square of the distance between the points S_{AB}^2 . To study the influence of technological parameters on the accuracy of determining the deflection of plumb lines, response graphs (Fig. 3-5) were constructed depending on the variable factor (other factors were at a constant basic level).

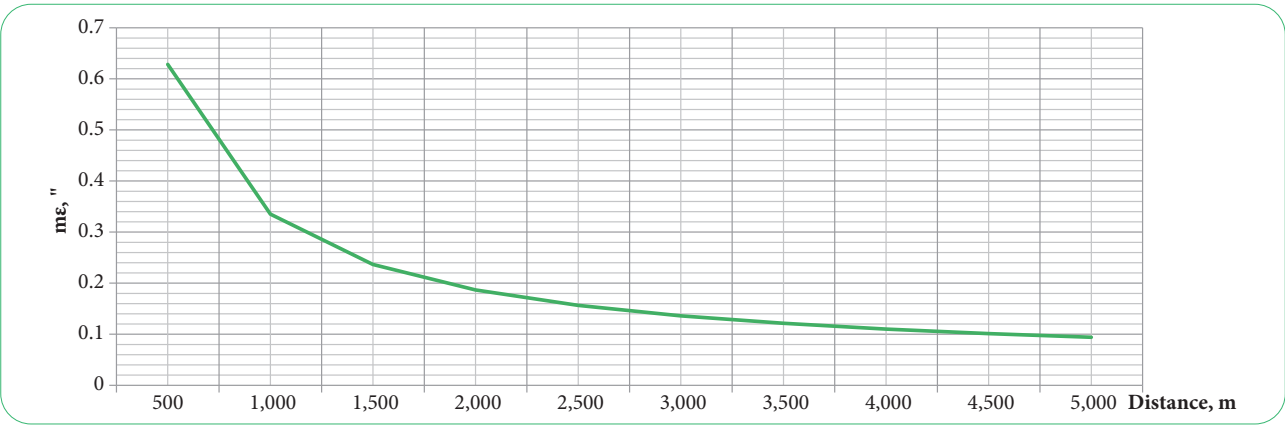


Figure 3. Calculation of the mean square error of determining the deflections of plumb lines depending on the distance between the site points for Method I

Note: the accuracy of determining geodetic elevations is 2 mm; the accuracy of orthometric elevations was calculated according to equation (2) taking into account the change in distance

Source: created by the authors

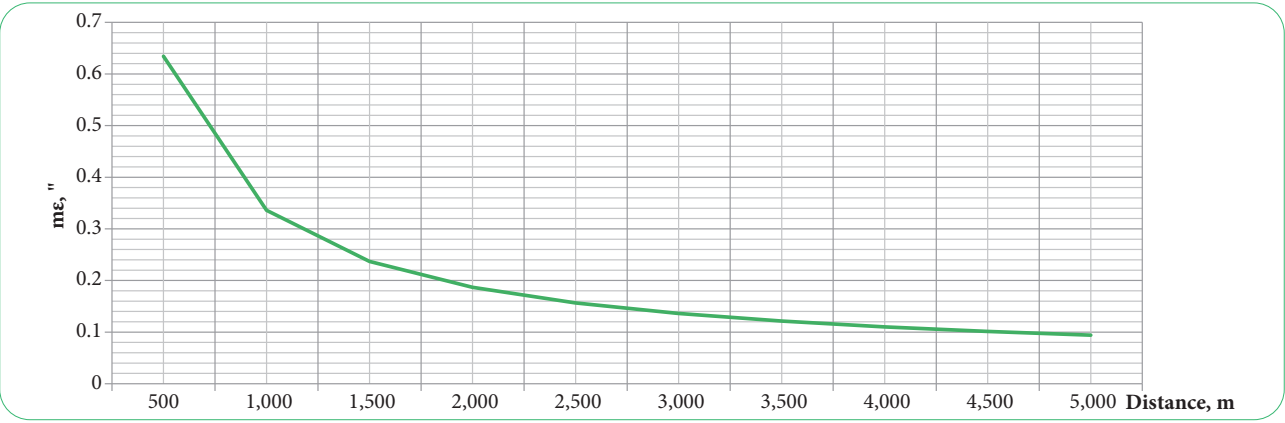


Figure 4. Calculation of the mean square error of determining the deflections of plumb lines depending on the distance between the site points for Method II

Note: the value of elevations between points is constant and is 50 m; the accuracy of determining geodetic elevations is 2 mm; the accuracy of orthometric elevations was calculated according to formula (2) taking into account the change in distance

Source: created by the authors

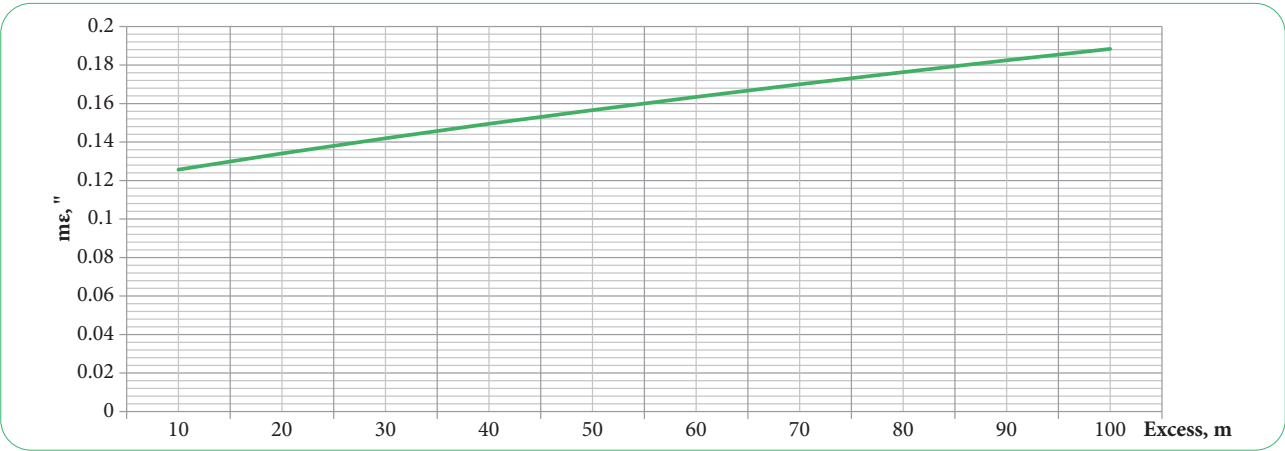


Figure 5. Calculation of the mean square error of determining the deflections of plumb lines depending on the elevations between site points for Method II

Note: the distance between the points is constant and is 2,500 m

Source: created by the authors

If with the help of precision levelling with a short beam $m_h = 0.5$ mm is reached, then already at distances from $S = 1$ km the deflection value of the plumb line from the normal will theoretically be $m_\varepsilon = 0.1''$. Visually comparing the graphs shown in Figure 3 and Figure 4, a significant similarity can be observed. Further correlation analysis of the arrays of data that led to such a result made it possible to obtain an indicator of 0.999998, which indicates a very high direct connection between the two investigated methods according to the Chaddock scale. Thus, each of the methods can be used in the practical field, and the results obtained by them will satisfy the existing limit requirements for accuracy. According to the Figure 5, it can be stated that the accuracy of Method II is also influenced by the height difference between the site points. This factor should be taken into account when building geodynamic sites in foothills and mountainous areas, where significant differences in altitude are possible. The proposed methods can be used for altitudinal support, namely the observation of neotectonic processes at geodynamic and man-made polygons, and the determination of land surface subsidence at mining observation stations located under residential areas or in the immediate vicinity of them, as they can ensure the relative accuracy of the results of 1×10^{-6} and higher and take into account the inhomogeneities of the gravity field.

✓ Discussion

In this work, research was carried out on the methods of determining the deflections of the plumb line from the normal and the methods of monitoring deformations of the Earth's surface, in particular in man-made destabilised territories. The results demonstrate the possibility of achieving high accuracy in determining these parameters, which is important for geodynamic research and ensuring environmental safety. Geodetic methods such as GNSS, InSAR, satellite gravimetry and laser location are becoming the main tools for monitoring the deformations of the Earth's surface. Iu. Karpinsky & N. Lazorenko-Hevel (2018) emphasised the importance of using modern technologies, such as the high-resolution orbital system, to produce accurate deformation maps and digital terrain models. They noted that the use of GNSS and InSAR allows obtaining global data on the Earth's gravity field and changes in the equipotential surface. The current study supports these findings by demonstrating high accuracy in determining plumb line deflections using GNSS and geometric levelling. At the same time, it has been established that the accuracy of the obtained data depends on the distance between the site points and the accuracy of determining geodetic elevations, which coincides with the conclusions of P. Dvulit *et al.* (2019).

The results obtained by V. Hlotov & M. Biala (2023) have shown the significant effectiveness of combined geodetic methods in monitoring deformation processes, in particular in man-made destabilised territories. They noted that the use of various methods, such as laser scanning and gravimetry, allows obtaining a more complete picture of the deformation processes. This study confirms these results,

especially in the context of the application of astro-geodetic levelling and GNSS to determine deflections of plumb lines. Attention is drawn to the importance of taking into account orthometric corrections in calculations, which is confirmed by the authors' calculations of the mean square error. The use of InSAR to monitor deformations of the Earth's surface has become an important component of modern geodetic research. Studies conducted by F. Raspini *et al.* (2018) have shown that InSAR can provide accurate measurements of continental-scale deformations, which is important for global monitoring of changes in the Earth's gravity field. The study also confirmed the effectiveness of InSAR in the context of deformation monitoring, especially in combination with other methods such as terrestrial gravimetry and GNSS. The use of InSAR can be particularly useful in cases where it is necessary to provide monitoring over large areas with high resolution. Differential equations have been developed to estimate errors in determining the deflections of plumb lines from the normal depending on various technological parameters. This helps to accurately assess the impact of the distance between site points and the accuracy of determining the elevations on the overall accuracy of the results.

The deflection of plumb lines is an important area of research, as it is directly related to the shape of the equipotential surface (geoid). The geoid is characterised by the same gravitational potential at all its points, and the direction of gravity is perpendicular to this surface. This affects the deflection of plumb lines, and therefore, by measuring them in different places, one can get valuable information about the shape of the geoid. This approach makes it possible to study the nature of the deformation of the Earth's surface and the dynamics of movement in general. The deflection of plumb lines from normals is a component of determining geoidal heights based on the results of high-precision levelling. This is due to the heterogeneity of the topographic masses and the influence of other factors, such as the local topography, anomalies on the terrain, parameters and position of the ellipsoid. Other studies, such as the work of G. Herrera-García *et al.* (2021) also proved the importance of taking into account topographic and gravity anomalies in the process of determining the deflections of plumb lines. They emphasised that these factors can significantly affect the accuracy of determining geoid heights, especially in regions with complex topography or anomalous geological conditions.

The most effective methods for determining geodetic heights are approaches based on the use of GNSS. Due to the significant development of GNSS technologies, it became possible to determine the deflection of plumb lines with an accuracy of $0.1-0.2''$ and changes in the shape of equipotential surfaces with mm accuracy. The difference in geodetic heights ΔH_{OP}^{geod} with the help of GNSS levelling can be determined with an accuracy of ± 2 mm in the post-processing mode of measurements, which corresponds to the development of the Astrogeodetic Network of Ukraine of Class I. The achievement of this accuracy was possible

thanks to the differential processing of the received data by the GAMIT/GLOBK method. Processing of the GNSS data include the use of precise satellite orbits, Earth orientation parameters, receiver clock and satellite clock corrections, and absolute phase centre variation models for receivers and satellite antennas. To accurately determine the shape of the equipotential surface, it is important to take into account the local topography, as well as to perform data processing using precise satellite orbits and Earth orientation parameters, as indicated in the research of H. Yuan *et al.* (2022). This makes it possible to obtain highly accurate results that reflect the real deformations of the Earth's surface and the dynamics of movement. The study has also developed technological parameters for obtaining optimal measurement results, namely: the distance between site points $S \geq 2$ km, the accuracy of determining geodetic elevations $\Delta H_{AB}^{GNSS} \leq 2$ mm, taking into account orthometric corrections and laying geometric levelling not lower than the Class I of accuracy. Given that the obtained data should be used to predict and minimise the risks associated with earthquakes and other adverse physical-geographical processes, which is directly related to the safety and livelihood of people, the developed technique provides an opportunity for additional control and evaluation of the results, which is a key advantage.

Researchers D.D. Basil *et al.* (2021) focused on the determination of deflection of vertical components using the integration of a global positioning system in the results of high-precision geometric levelling on the studied site. The obtained results were compared with the use of gravimetric models (EGM2008, EGM1996, EGM1984). Despite the obtained high results, the authors did not take into account the possible presence of anomalies on the territory of the site, or the heterogeneity of the Earth's masses, assuming that orthometric elevations will be equal to the results of geometric levelling. A comparative analysis of modern models of plumb line deflection has demonstrated that, despite the high overall accuracy of parameter determination, some models may have significant errors in individual regions. The data analysis has showed that the accuracy of models can vary depending on the regional features of the geoid and gravity field. For example, in regions with a complex geodetic profile or with significant local anomalies of the gravity field, the accuracy of the models may decrease. This is due to the fact that global models do not always take into account all local geodetic and gravity features. The studies by H. Yuan *et al.* (2022) proved that the EGM2008 model showed slightly higher accuracy in some regions compared to EIGEN-6C4, especially in regions with intense geodynamic processes. However, EIGEN-6C4 proved to be more accurate in regions with lower gravity variability. This indicates that the choice of model for specific geodetic problems should be based on the characteristics of the region where the measurements are made. Thus, modern geoid models such as EGM2008 and EIGEN-6C4 demonstrate high overall accuracy, but their performance may vary depending on regional features. To ensure the highest accuracy in

specific regions, it is recommended to perform local corrections and analysis of data obtained using ground-based methods for determining the deflection of a plumb line.

G. Herrera-García *et al.* (2021) noted that the use of GNSS for monitoring neotectonic processes allows obtaining accurate data on the displacement of the Earth's surface in real time. However, this method requires the installation of stationary stations, which can be expensive and technically difficult in remote areas. The scientists also state, as it is shown in their study, that the primary task in investigating neotectonic processes is to create a network of regional geodynamic sites and develop methods that allow determining the deflection of a plumb line from the normal with an accuracy of $\pm 0.2''$ or a change in the shape of the geoid with an accuracy of up to 5 mm (Procedure for Building the State Geodetic Network, 2013). This approach has not been implemented in previous studies and is an important contribution to the field of geodesy and deformation monitoring. Thus, current article proposed a methodology and substantiates the technological parameters that can be used for studies of changes in the shape of the equipotential surface on geotechnological sites, ensuring the accuracy of determining the deflection of plumb lines of $0.2''$ and taking into account the inhomogeneity of the gravitational field. It is proved that methods of ground gravimetry, such as relative and absolute gravimetry, can be effective for determining local changes in the Earth's gravity field. The results confirm and extend previous studies in the field of Earth surface deformations.

✓ Conclusions

The study of determining the deflections of plumb lines and their influence on ground geodetic measurements has led to the following results. A comparative analysis of plumb line deflection models has showed that modern models provide high accuracy in determining parameters, but may have significant errors in certain regions. An improved method of determining plumb lines deflections has been developed based on the use of GNSS observations and data on the vertical component of the gravity potential at reference points. This technique makes it possible to increase the accuracy of determining the deviation of the vertical line, reducing the impact of systematic errors associated with not taking into account the hypsometric component during measurements. A significant advantage of the proposed methodology is the ability to control measurement results due to the comparison of geodetic elevations obtained directly from GNSS measurements and from the results of ground measurements.

The technological parameters for the construction of geodynamic sites and the improvement of precision measurements carried out on them have been developed. The implementation of these recommendations helps to increase the efficiency and accuracy of work, reducing the time and resources spent on adjusting measurement results. Detailed calculation formulas (13) and (14) have been developed to assess the accuracy of determining the deflection of plumb

lines. These formulas take into account the accuracy of the difference in geodetic heights obtained from precise GPS measurements. They also take into account hypsometric elevations, which are defined as the difference in height between two points, taking into account corrections for the curvature of the Earth's surface and other geodetic factors. In addition, the formulas take into account the distances between the observation stations, since a larger distance between the stations can increase the influence of local anomalies of the gravity field. All these components are taken into account not only in terms of their accuracy, but also their actual values, which makes it possible to achieve high accuracy when determining the deflection of plumb lines. The proposed Method I and Method II can be used to study changes in the shape of the equipotential surface on

geotechnological sites, as they ensure the accuracy of determining the deflection of plumb lines of 0.2" and take into account the inhomogeneity of the gravitational field while observing the obtained technological parameters. In future research, it is worth focusing on the approbation of the developed methods on the network of observation stations of the Kalush-Holyn Deposit and the impact study of the gravity field inhomogeneity on the height determination accuracy in the area with a non-homogeneous gravity field.

✓ Acknowledgements

None.

✓ Conflict of Interest

None.

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Оцінка наземних методів моніторингу неотектонічних процесів на геодинамічних полігонах

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✓ **Анотація.** Актуальність роботи полягає у необхідності вдосконалення методів моніторингу неотектонічних процесів та розробленні технологічних параметрів для забезпечення більш ефективного прогнозування геодинамічних явищ. Точний моніторинг неотектонічних процесів є важливим для оцінки змін геологічних умов та попередження потенційних ризиків, що впливають на екологічну безпеку та безпеку життєдіяльності людини. Метою дослідження була оцінка ефективності різних наземних методів моніторингу неотектонічних процесів для визначення їхньої надійності та точності. У дослідженні використано методи, зокрема геодезичні вимірювання, які забезпечують високу точність та достовірність результатів; геофізичні методи, що дозволяють виявити підповерхневі структури та процеси; а також дистанційне зондування Землі, яке забезпечує широкомасштабний моніторинг та аналіз динаміки неотектонічних явищ. Проаналізувавши існуючі методи визначення зміни форми еквіпотенціальної поверхні, виявлено та обґрунтовано переваги використання геодезичних вимірювань для забезпечення точності та достовірності результатів вимірювань. Запропонована методика ґрунтується на дослідженні зміни форм еквіпотенціальної поверхні на геотехногенних полігонах та враховує неоднорідність гравітаційного поля, а при дотриманні розроблених технологічних параметрів забезпечує визначення відхилення прямовисних ліній із точністю $\pm 0,2''$. Результати дослідження показали, що комбінування цих методів дозволяє отримати більш комплексну картину неотектонічних процесів, що також сприяє більш точному прогнозуванню та запобіганню наслідків геодинамічних явищ. Запропонований підхід до моніторингу неотектонічних процесів може бути використаний для розробки ефективних стратегій моніторингу та управління екологічними ризиками, пов'язаних із геологічними небезпеками

✓ **Ключові слова:** гіпсометричні перевищення; ортометрична поправка; геоїд; відхилення прямовисної лінії від нормалі; геометричне нівелювання; GNSS-спостереження

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