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Assessment of the ecological status of soil cover and design of environmental monitoring in the Ivano-Frankivsk urban community

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Abstract. Due to the increasing technogenic load on the environment, it is necessary to determine the degree of influence of industrial production on the environment. Conducting environmental monitoring of the Ivano-Frankivsk urban amalgamated territorial community will allow for further ecological assessment and forecasting of the environmental status of the studied territory. The aim of the study was to assess the condition of the soil cover of the Ivano-Frankivsk urban community and its surroundings, to determine the relevance of using geographic information systems (GIS) in environmental monitoring. The research used: a statistical method for collecting and analysing databases on the environmental situation with pollution of environmental components; and GIS mapping to identify and display the spread of pollutants using the Kriging interpolation method. A detailed analysis of various methods for monitoring the environmental status has been conducted, including remote and chemical methods. This allowed for identifying the most effective approaches for collecting and processing environmental data. Important aspects of creating an environmental monitoring system for tracking the state of the environment have been considered. Based on the collected data, maps have been created that reflect the distribution of chemical elements in the territory of the Ivano-Frankivsk urban amalgamated territorial community. These maps are an important tool for visualising and analysing the ecological status of soils. A variant of building an environmental monitoring system has been proposed and a project cartographic model has been developed. This will allow for more effective environmental monitoring and planning of measures to improve the ecological status of the area. The use of MapInfo and Surfer software allowed for a detailed analysis of the environment and the creation of a geographic information system for environmental monitoring of the Ivano-Frankivsk urban community. The results of the study have significant practical implications for various fields of environmental management and planning, including for conducting further environmental monitoring, for the spheres of state and local environmental management, public initiatives, and educational programmes

Keywords: geographic information systems; cartography; technogenic impact; field research; concentration coefficient

Introduction

Environmental protection issues are becoming increasingly urgent and pressing. The growth of industrial production, technogenic load, and other anthropogenic impacts negatively affect the environment, especially in cities. Therefore, conducting environmental monitoring and assessing the impact of anthropogenic factors on the urban environment is an extremely important task. Environmental monitoring is a system of continuous monitoring of all environmental components in space and time, accumulating geographic information data on the past and current state of the

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environment. Forecasting changes in environmental parameters under anthropogenic influence using a territory's ecological monitoring system allows for identifying and analysing the state of the environment, which is crucial for biota. Modern challenges associated with climate change, land degradation, and water and soil pollution require new approaches and solutions to preserve the environment and ensure sustainable development. Environmental monitoring using geographic information systems (GIS) and modern technologies is an important research direction that is actively advancing worldwide.

Various international and national institutions, such as UNESCO, the European Environment Agency (EEA), and the National Aeronautics and Space Administration (NASA), actively use satellite data and GIS for monitoring the ecological status (Copernicus, n.d.; Applying NASA data…, n.d.). For example, NASA employs satellite technologies to track climate change, land degradation, and the state of water resources, while the EEA focuses on analysing data on air, water, and soil pollution in Europe. In Ukraine, research in this field is conducted by scientific institutions and individual researchers, including the Research Institute of Geodesy and Cartography and the Institute of Telecommunications and Global Information Space of the National Academy of Sciences of Ukraine. Significant contributions to the development of environmental monitoring methods have been made by researchers such as V. Trysnyuk & Ye. Nahornyy (2024), studied the use of information technologies for processing radioactive contamination data, and O. Trofymchuk *et al.* (2020), analysed hazardous processes in the geological environment and issues of environmental safety.

Recent publications on the use of GIS in environmental monitoring can be found in academic journals, conference proceedings, and scientific collections. The publication by P.K. Badapalli *et al.* (2022) explores various applications of GIS in tracking and assessing the state of the environment. This is relevant due to the deepening problem of land degradation and desertification in semi-arid regions. The use of modern data collection and analysis methods, such as Landsat 8 operational land imager and thermal infrared sensor, land surface temperature, and normalised difference vegetation index, allows for efficient detection and tracking of changes in the ecological state of territories. This enables the development of strategies and measures to prevent soil degradation and desertification, as well as ecosystem restoration. The research by Y. Anpilova *et al.* (2020) reflects the relevance of using modern data analysis methods, including ground-based interferometry, for monitoring geological structures. The use of GIS allows for more accurate assessments of the impact of the Solotvyno agglomeration mines on the environment and life support systems in the transboundary basin of the Tisza River. Analysis has shown a mathematical relationship between surface deposits and their radial increase, which is crucial for risk forecasting and safety enhancement. Current research at the Institute of Telecommunications and Global Information Space covers a wide range of topics. Key research areas include the use of GIS and Earth remote sensing technologies, mathematical modelling methods and the solution of urgent environmental safety problems (Trofymchuk *et al.*, 2020). Among them, it is important to note the study of hazardous processes in the geological environment and soils, in particular, particularly issues related to landslides. The use of satellite technologies, the detection of soil degradation, and the timely response to these processes require timely information and the availability of a database. The ecological safety system aims to predict and prevent technogenic and ecological emergencies, as noted by O. Butenko *et al.* (2020).

In the Ivano-Frankivsk Region, there is a diverse soil cover consisting of natural and technologically transformed soils. General soil degradation in urban systems occurs under the influence of urban air and hydrosphere. Despite the natural capabilities of biological self-purification of the soil, its mechanisms can be seriously disrupted by overloading with various types of pollution. A particular problem in the cities of Tysmenytsia and Ivano-Frankivsk is the presence of a cultural layer, which contains traces of human activity and various pollutants. These layers, as objects of historical and archaeological study, contain a large amount of various pollutants that negatively affect the soil cover and the natural environment. In this regard, conducting environmental research and monitoring the state of the soil cover is of great importance for preserving the environmental sustainability of the urban environment. In this context, this study aimed to conduct field ecological research to investigate the ecological state of the Ivano-Frankivsk urban amalgamated territorial community (UATC) and identify possible ways to improve it. In particular, the study investigated the state of the soil cover in the Ivano-Frankivsk urban community and the application of GIS in further monitoring of this region.

Materials and Methods

To determine the technogenic impact, it is necessary to first understand the scale of the study; in this research, it is the Ivano-Frankivsk UATC. Considering the specific features of the geological structure, geomorphology, distribution of different soil types, landscape structure of the territory, and the requirements for the scale of research, an environmental monitoring network was established comprising 6 profiles and 117 geo-ecological polygons – observation points on a plot of about 265 km^2. These points are evenly distributed across the entire study area. The scale of the research is 1:100,000 (Fig. 1). The geographic coordinates and absolute heights (altitudes) of the points were determined using a GPS device eTrex 30, which used Garmin Custom Map user maps and satellite imagery. The operating modes of the eTrex 10 allowed for the creation of accurate routes to simplify orientation on the terrain, as well as the use of 3D mode.

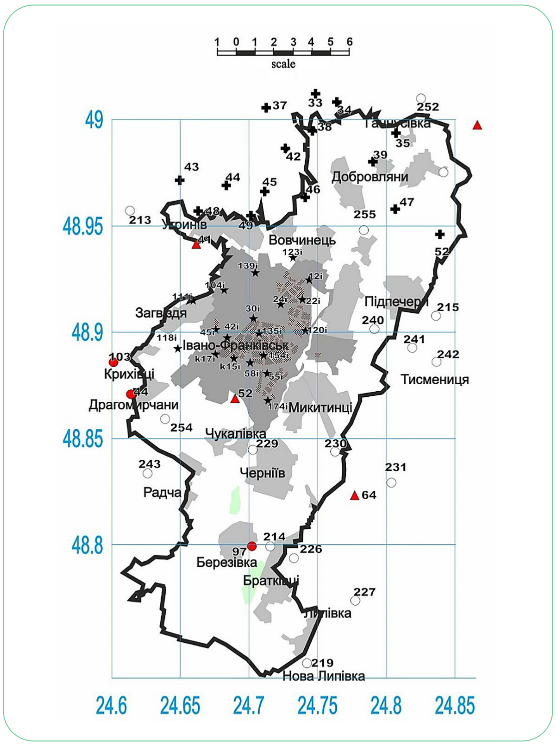

Figure 1. Map of the factual material
Source: created by the author

The goal of the field ecological studies was to create geographic information maps and study soil disturbances based on analysis and observation to compile maps of soil pollution distribution. During the routes, soil samples were collected. The main focus was on enterprises with discharges and emissions, railways and motorways, etc. Field studies were carried out using parallel routes and loops, which were linked to the type of landscape. Ecological studies of parallel routes were used to create ecological maps with pollution zones that have a north-south orientation in the study area. Therefore, the research routes were laid out from the southeast to the northwest and vice versa, as well as from the southwest to the northeast. These routes were laid out along forest clearings, paths, field boundaries, and other objects on the map. The essence of the radial-loop method lies in the fact that the route polygon was divided into parts that were studied in circular and radial directions. The radial-loop method allows for a detailed study of the soil cover, studying complex landforms, digitising the impact of pollution sources, and degradation of the geological environment. Thus, with the help of field expeditionary research, the entire territory of the studied polygon within the Ivano-Frankivsk urban community was evenly studied.

Sampling points for various analyses were located on profile lines of routes every 0.5-2 km. Samples were taken at three sites to determine the input of pollutants into the soil. The sampling procedure was carried out in a network corresponding to the district-level study scale (1:100,000). A mandatory condition was the indication of geocoordinates, physical and geographical characteristics, date, and time of sample collection. Samples were collected using an envelope scheme measuring 5×5 m and combined into a single sample, whenever possible, at least 50 m from the road in an open area. On intact soils, sampling was carried out from a depth of 10-20 cm. On anthropogenically altered soils where undisturbed lands were absent, samples were taken at a depth of 20-30 cm. Rock fragments, aboveground and root parts of plants were removed from the sample. The weight of the soil sample was 1.5 kg. Samples were taken using a drill with a 50 mm diameter metal cup in accordance with the use of landscape, geomorphological, and soil maps to cover all types of zonal soils with an appropriate grid. In total, 117 soil samples were taken at geo-ecological polygons. Analyses of the samples were carried out in the universal laboratory of Ivano-Frankivsk National Technical University of Oil and Gas, at the Department of Ecology, using Fourier IR spectrometer FSM 1201 (Ukraine) designed for measurements and scientific research in the mid-infrared spectral region. The pedosphere was assessed from two positions: from an ecological standpoint, characterised by changes in soils, their degradation, and pollution, and a general characteristic that covered the spatial distribution of the main soil types according to D. Zorin (2023).

Based on the obtained analysis results, databases were created in Microsoft Excel and then in MapInfo Professional, which are needed for the interpolation of ecological maps in Surfer. The first step was to calculate all isoconcentrates in Microsoft Excel to determine anomalous and background concentrations in soils to assess the degree of pollution relative to the clarke concentration. To determine background concentrations *B*, the contents of elements C_i are grouped by characteristic intervals into columns of the table, and for each ranked row of the column, the average content of all intervals of the element is calculated. The background was determined for each chemical element in the soil. To do this, it is necessary to determine the nature of the content of the pollutant in most (2/3) of the samples, that is, 66.6%, after which the average content of these indicators is determined. Anomalous values of C_a are concentrations that are 3 times higher than the background. Based on the background values, the total pollution indices (TPI) are calculated. TPI is the sum of the concentration factors, and the concentration factor is the ratio of the concentration to the background or maximum permissible concentration (MPC) (Zhou & Li, 2021; Arkhypova *et al.*, 2021; Adamenko *et al.*, 2022):

$$Z_c = \sum_1^n \frac{C_i}{C_f}, \quad (1)$$

where Z_c is the TPI; *n* is the number of indicators used for calculating the index; C_i is the concentration of the chemical element; *B* is the background level. These calculations enable the construction of interpolation maps of soil contamination according to the corresponding isoconcentrates. Anomalous content is defined as anything that exceeds the background level by three times.

$$C_a = C_i - B - C_c, \quad (2)$$

where C_a is the anomalous content; C_i is the concentration of the chemical element in the soils; B is the background level; C_c is the clarke concentration. The interpolation of ecological maps showing the distribution of a particular element in the soils of the Ivano-Frankivsk urban community was plotted on the map with isoconcentrate lines – *ik*. The average content of the ranked series of concentrations in each characteristic interval corresponds to the arithmetic mean value of that interval. This value can be used to characterise the average level of concentration of a chemical element within a defined range.

Results

In the Ivano-Frankivsk Region, there is a developed soil cover, which consists of natural and technogenically transformed soils. The soils of urbanised areas are subject to the same negative impacts as urban air and hydrosphere. Even though the soil has certain capabilities for biological self-purification, it breaks down and mineralises the waste that enters it. The mechanism of this process can be disrupted due to its overload (physical, chemical, mechanical), which leads to degradation. In the Tysmenytsia and Ivano-Frankivsk, the so-called cultural layer (transformed soils) is most common, in which traces of human activity are found: broken bricks, glass, plastic products, construction debris, fragments of concrete, clay shards, and wood. Cultural layers in cities are objects of historical-archaeological and geological study. They also concentrate mechanical, chemical, biological, and radioactive pollution. Therefore, cultural layers should also be mapped and studied by soil scientists and ecologists. Such soils are characterised by compaction, which worsens air exchange, leads to nitrogen starvation of green spaces, and suppresses the activity of soil microorganisms. A large amount of technogenic material is characterised by increased drainage, deteriorates the nourishment of plants, especially trees, and disrupts the water environment. Burning leaves can harm the functioning of park phytocenoses, as it disrupts the main geochemical cycle of nutrient return to the soil. The results of the analysis of 117 soil samples by the Ivano-Frankivsk Regional Sanitary and Epidemiological Station are summarised in the database (Table 1).

Table 1. Database of soil sample analysis in the Ivano-Frankivsk UATC

No.	Sample No.	Element content, mg/kg, C_i						TPI
		gross			mobile		gross	
		Hg	Cd	Pb	Cu	Zn	Ni	$Z_c = \sum_1^n \frac{C_i}{C_f}$
	Background→	0.001	0.011	1.5	0.44	3.5	0.24	
	MPC→	2.1	1.0	20.0	3.0	23.0	4.0	
1	● 22	0	0	0	0	0.001	0	0.00013
2	○ 201	0.9	1.2	20.3	3.6	18.4	0	403.8864
3	▲ 50	0	0	0	0.001	0.006	0	0.006665
4	● 23	0	0	0.001	0	0.04	0	0.006392
5	○ 202	–	0.001	0.007	0	0.03	0	0.262147
6	○ 203	2.2	1.3	16.4	.1	16.2	0	0.262147
7	○ 204	–	–	–	–	0.3	–	0.262147
8	○ 210	0	–	0.04	–	0	0	0.047059
9	○ 211	0	–	0.1	–	0	0	0.117647
10	● 32	0.007	–	0.2	0.01	0	0	1,587.398
11	○ 212	2.5	1.6	24.2	3.5	24.1	4.6	510.6136
12	○ 213	0	–	0.3	0.03	0.004	–	0.529933
23	○ 243	0.03	0.004	0	0.03	–	1.70	25.8352
24	○ 254	0.007	0.001	4.75	0.07	1.30	1.70	216.4139
25	● 44	0.01	0.004	0	0	0.2	0	1,001.098
26	▲ 52	0.04	0.003	0	–	–	0	245.334
27	○ 206	0.001	0	0	–	–	0	0.007143
28	▲ 42	0.06	0	0	–	–	0.57	2,614.204
29	○ 207	–	–	4.90	0.30	3.50	0.57	11.6524
30	○ 208	0.01	–	0.03	–	0	0	0.106723
31	○ 209	0.003	–	0.06	–	0	0	0.092017
32	★ K17i	2.3	0.9	14.2	2.8	24.3	5.6	708.8843
33	★ 111i	1.6	2.1	12.8	1.9	18.9	4.9	3,892.35
34	★ 139i	2.1	1.4	24.6	3.2	16.6	7.2	1,754.929
35	★ 12i	2.4	1.2	31.2	4.2	29.2	8.4	744.0283
36	★ 24i	0.8	0.8	36.6	1.9	24.4	5.4	748.1308

Table 1. Continued

No.	Sample No.	Element content, mg/kg, C_i						TPI
		gross			mobile		gross	
		Hg	Cd	Pb	Cu	Zn	Ni	$Z_c = \sum_1^n \frac{C_i}{C_f}$
	Background→	**0.001**	**0.011**	**1.5**	**0.44**	**3.5**	**0.24**	
	MPC →	**2.1**	**1.0**	**20.0**	**3.0**	**23.0**	**4.0**	
37	★ 45i	1.6	1.1	24.9	2.8	19.6	4.6	2,560.304
38	★ 174i	1.4	1.3	41.2	3.1	18.1	4.9	5,081.288
39	★ 58i	0.7	1.2	46.3	3.5	24.7	9.2	1,184.39
41	★ 104i	0	0	0	0.1	0.03	0.001	5.597702
42	★ 42i	0	0	0	0.4	0.06	0.009	32.41076
43	★ 22i	0.001	0.004	0.001	0.7	0.2	0.006	25.18538
44	★ K15i	0.003	0.001	0.004	0.03	0.9	0.01	5.625501
45	★ 55i	0	0	0.001	0.001	0.2	0.04	50.25536
46	★ 154i	0	0	0.01	0.07	0.8	0.06	100.8612
47	★ 120i	0	0	0.06	0.2	0.004	0.003	16.26425
48	★ 123i	0.009	0.003	0.9	0.1	0.001	0.001	22.46703
49	★ 30i	0.04	0.001	0.4	0	0	0	46.0063
50	★ 118i	0.01	0.01	0.03	0	0	0	52.60672
96	+ 40	0	0.01	1.4	0.2	1.1	0	5.466945
97	+ 41	0	0	0.3	0.6	1.3	0	4.051844
98	+ 42	3.6	1.4	18.4	6.8	39.7	3.9	2,614.204
99	○ 248	–	–	0	0	0.04	0	
100	+ 47	0	0.01	1.4	0.6	1.5	0	7.872038
101	+ 52	2.0	0.06	31.7	2.6	30.8	4.4	1.035714
102	○ 249	–	0.001	0	0	0	0	0.47858
103	○ 250	–	0.004	8.05	0.2	2.4	0.23	13.73774
113	○ 251	0.006	–	3.8	0.23	1.6	0.73	10.63055
114	+ 27	0	0.05	1.6	0.2	0.6	0	15.63705
115	+ 28	0	0.03	1.3	0.1	0.5	0	9.682836
116	○ 252	2.4	0.001	16.8	2.9	24.3	–	122.3846
117	○ 253	0.004	–	2.6	< 0.005	2.2	1.06	9.792527
	isoconcentrates (*ik*) for interpolating pollution on maps	0	0	0	0	0	0	
		0.003	0.002	0.005	0.004	0.003	0.004	
		0.009	0.004 *B*	0.05	0.09	0.047	0.05	
		0.014 *B*	0.008	0.54	0.17 *B*	0.93	0.18 *B*	
		0.042 *a*	0.012 *a*	0.82 *B*	0.42	4.0	0.54 *a*	
		0.15	0.03	2.3	0.51 *a*	7.67 *B*	0.66	
		1.4	0.9	2.46 *a*	1.4	18.3	2.0	
		2.1 MPC	1.0 MPC	11.5	2.5	23.0 *a* MPC	4.0 MPC	
		2.6	1.4	20 MPC	3.0 MPC	30.3	5.8	
		–	–	30.7	4.1	–	–	

Note: ○ 253 sampling points of the Tysmenytsia Environmental Monitoring System (EMS); + 47 sampling points in the territory of Private joint stock company "Ivano-Frankivskcement"; 97 sampling points of the Bohorodchany gas transportation node; ▲ 52 sampling points of the Ivano-Frankivsk Regional EMS; ★ 22i sampling points of the Ivano-Frankivsk urban EMS; B – background values; a – anomaly
Source: compiled by the author

The worst soils have an unsatisfactory ability to remove toxic chemical elements such as Hg, Cu, Pb, F, Mn, and others. These elements gradually spread throughout the soil cover and accumulate, especially near industrial emission sources. For instance, in areas near superphosphate and mercury plants, 1 kg of soil can contain from 1.3 to 5.6 mg of mercury. In soils with a pH below 5.0, the mobility of elements such as Cu, Cd, and other heavy metals increases. Some microorganisms found in the soil can convert heavy metal salts into various forms – soluble or insoluble, which affects the disruption of trophic links and can lead to the disappearance of invertebrates. Negative impacts on soils are caused by radionuclides, phenols, petroleum products, and pesticides. On private and summer cottage plots, excess mineral fertilisers quickly spread throughout the territory, significantly worsening the conditions for the development of plant plantations. Significant loading of soils by vehicles, as well as the impact of anthropogenic influence, lead to their compaction: if the norm is 10 kg/m^2, then in places of active recreation it increases to 30-40 kg/m^2 and reaches a depth of 30 cm, which leads to a deterioration in soil quality. During ecological studies of the soil cover of the Ivano-Frankivsk urban community, all these features should be taken into account. The determination of anomalous and background concentrations in the soils was carried out. Table 2 shows the calculations of *B*, and C_a for the interpolation of C_i.

Table 2. Calculations of *B*, C_a for interpolating C_i of eco-technogeochemical soil maps with isolines of equal concentration levels

Intervals of content					
0	**0.001-0.005**	**0.006-0.01**	**0.02-0.1**	**0.2-2.0**	**> 2.0**
0	0.001	0.01	0.03	0.9	2.2
0	0.004	0.007	0.04	1.6	2.3
0	0.003	0.01	0.04	0.8	2.1
-	0.001	0.009	0.06	1.6	2.4
-	0.003	0.01	0.06	1.4	2.3
-	0.001	0.01	0.03	0.7	2.5
-	0.003	0.007	0.9	1.9	3.4
-	0.003	0.01	0.02	1.6	2.2
-	0.002	0.01		1.6	2.3
-	0.001	0.01		1.4	3.6
-	0.003	0.01		1.9	2.4
-	0.001			1.7	3.9
-	0.004			2.0	
0	0.003			1.6	
0	0.006			0.9	
0	0.004				
$\sum_{n=1}^{47} = 0$	$\sum_{n=1}^{16} = 0.043$	$\sum_{n=1}^{11} = 0.103$	$\sum_{n=1}^{8} = 1.18$	$\sum_{n=1}^{15} = 21.6$	$\sum_{n=1}^{12} = 31.6$
$\overline{x} = \frac{0}{47} = 0$	$\overline{x} = \frac{0.043}{16} = 0.0027$	$\overline{x} = \frac{0.103}{11} = 0.009$	$\overline{x} = \frac{1.18}{8} = 0.15$	$\overline{x} = \frac{21.6}{15} = 1.4$	$\overline{x} = \frac{31.6}{12} = 2.6$
$ik = 0$	$ik = 0.003$	$ik = 0.009$	$ik = 0.15$	$ik = 1.4$	$ik = 2.6$
B (82 out of 117 parameters, i.e., 66.6%) $= \frac{0+0.043+0.98}{47+16+9} = 0.014$ $a = 3 \times B = 3 \times 0.014 = 0.042$ *ik* for map interpolation: 0 – 0.003 – 0.009 – 0.014 – 0.042(*B*) – 0.15(*a*) – 1.4 – 2.1(MPC) – 2.6					

Source: created by the author

Technogenic impact and environmental pollution lead to the transformation and changes of landscapes. By quantitatively assessing these changes, it is possible to determine the ecological state of individual components of the ecosystem (landscape), or its entirety, by analysing geochemical coefficients (Moss *et al*., 2020; Bilas *et al*., 2022). Several methodological approaches to assessing the ecological state have been proposed by various authors, but they all depend on the amount of analytical material that characterises the degree of geochemical research of a specific territory. The more analyses of soils, water, air, and vegetation are carried out, the more accurately the ecological state of the landscape can be assessed. Indicators of such an assessment include concentration factors, pollution indices, and other parameters. Calculating these quantitative indicators allows for evaluating the degree of environmental changes, which can be categorised as normal (favourable), satisfactory, tense, complex, unsatisfactory, pre-crisis, critical, or catastrophic (Lysytsia & Mudrak, 2022).

In each component of the landscape (for example, soil, water, air, etc.), various chemical elements can be found, which at certain concentrations are not harmful to humans, and are even beneficial and necessary. The average concentration of elements in the Earth's crust (lithosphere) is considered a clarke value (Table 3). Similar clarke values are calculated for soils, water, etc. However, in each region, depending on the geological structure, soil type, geographical zoning, and other factors, there will be its own, characteristic only for this region, average content of elements. Such average content is known as a regional background. It can be greater or less than the clarke values, depending on specific conditions (Adamenko *et al*., 2022).

Table 3. Clarke values of the lithosphere

Element	Clarke values	
	%	mg/kg
Hg	8.3×10^{-6}	0.0083
Cd	1.3×10^{-5}	0.13
Pb	1.6×10^{-3}	16
Cu	4.7×10^{-3}	47
Zn	8.3×10^{-3}	83
Ni	5.8×10^{-3}	58

Source: compiled by the author based on I. Klymchuk *et al.* (2022)

Therefore, if there is an excess of the clarke values, and subsequently the background, the concentrations will be anomalous and harmful to the normal development of ecosystems. Toxic, i.e. harmful to the human body, contents of a particular element in the Ivano-Frankivsk urban community are values that exceed the MPC. Clarke concentrations are the ratio of the average content of a particular chemical element in the environment, or any object in nature, compared to some standard or baseline value. Clark concentrations are represented by known data (Table 3), while the background was calculated based on specific factual material, which is reflected in Table 2.

For accurate interpolation of elements on maps of geochemical environmental pollution, isolines are drawn through characteristic intervals, rather than arbitrarily. This approach allows for more accurate and representative results by accounting for concentration variations within defined ranges. Only such a construction of cartographic material will convey the nature of the distribution of the element in the environment. The map must necessarily include isolines of a ranked series, background, anomalous values, MPC, and maximum concentrations from the database to justify the characteristic distribution of the concentration of a particular element in its intervals. Such interpolation must be carried out for each element in order to study all the features of their distribution in soils and accumulation in the studied area. Elemental eco-geochemical maps of the content of various elements in soils and maps of TPI are generated using data interpolation in automatic mode on a PC, using the Surfer (Fig. 2-8).

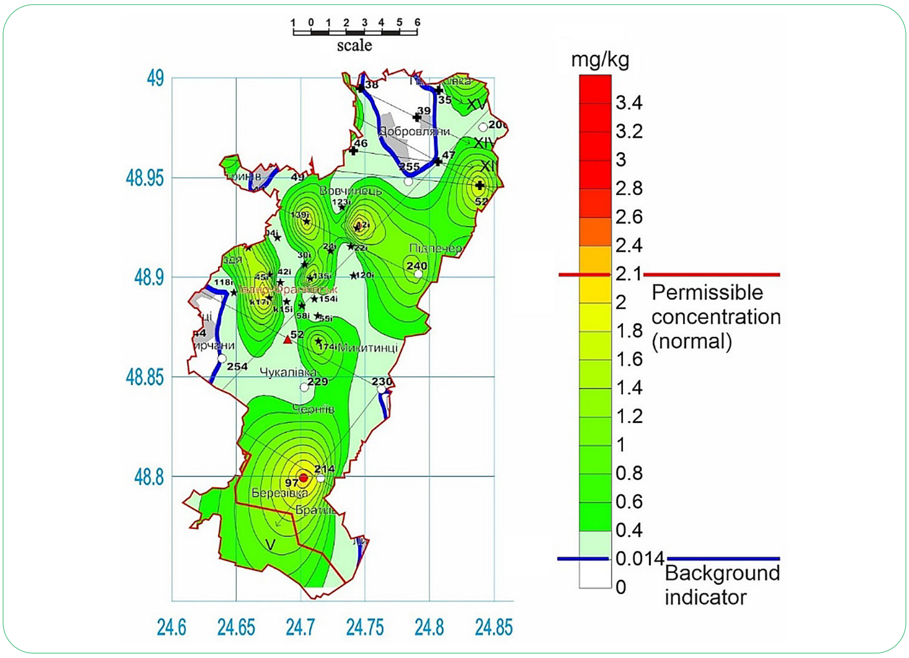

Figure 2. Hg concentration, mg/kg of soil

Source: created by the author

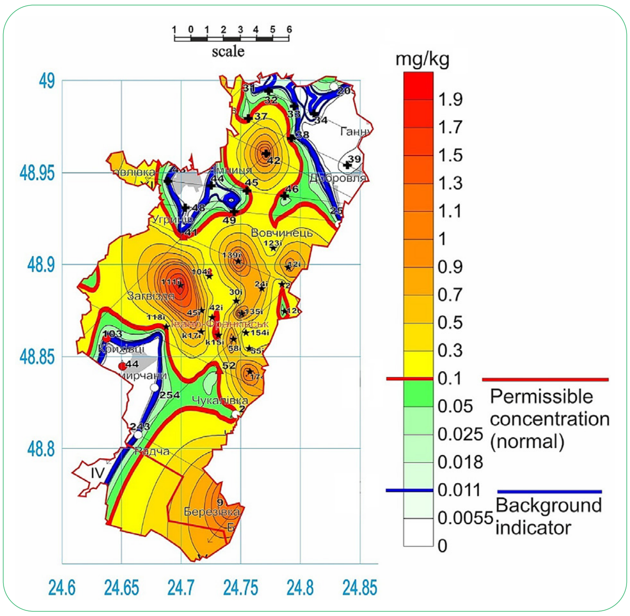

Figure 3. Cd concentration, mg/kg of soil

Source: created by the author

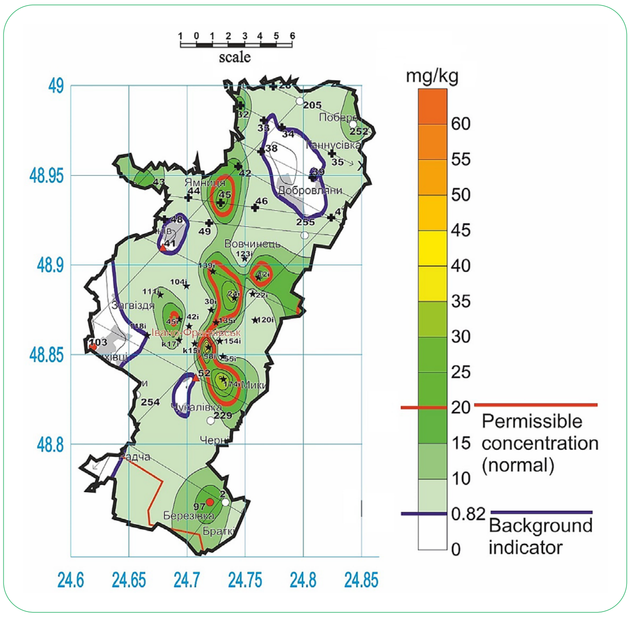

Figure 4. Pb concentration, mg/kg of soil

Source: created by the author

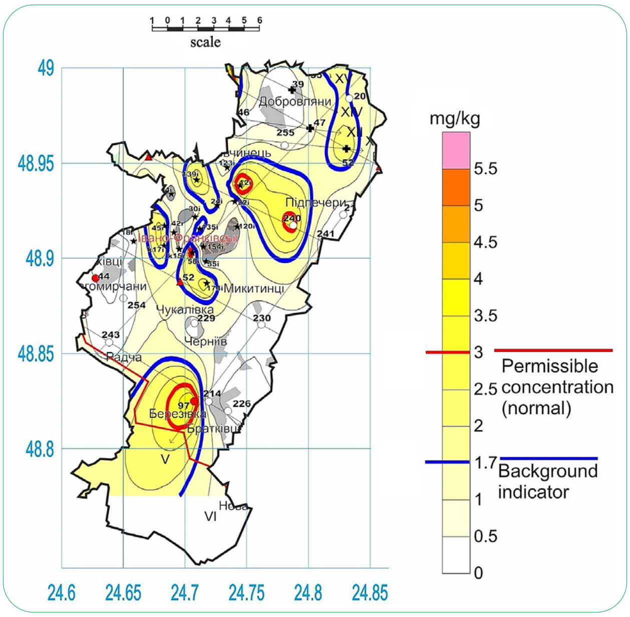

Figure 5. Cu concentration, mg/kg of soil

Source: created by the author

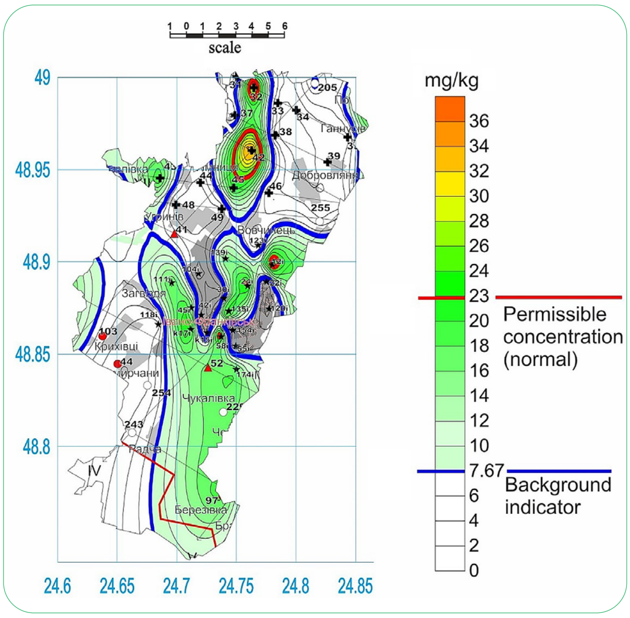

Figure 6. Zn concentration, mg/kg of soil

Source: created by the author

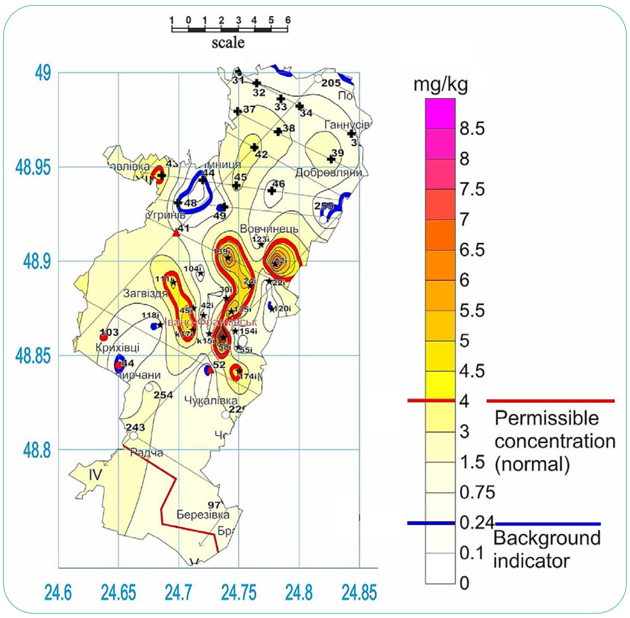

Figure 7. Ni concentration, mg/kg of soil

Source: created by the author

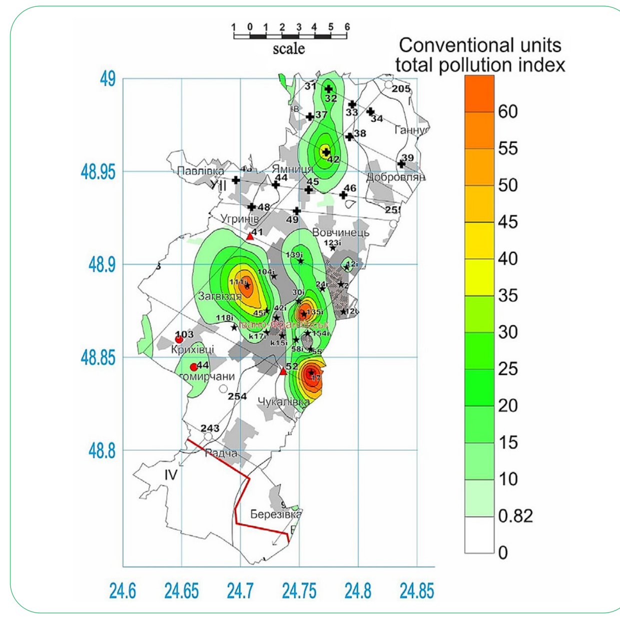

Figure 8. Soil TPI

Source: created by the author

The map of soil TPI (Fig. 8) shows the distribution of zones within the Ivano-Frankivsk UATC where there is an excess of background values and where the MPC is exceeded. Interestingly, when comparing these zones with the routes of main gas pipelines, the locations of compressor stations, and underground gas storage facilities, their interconnection can be detected. However, there are such pollution zones where technogenic sources are unknown. The authors of the study believe that for final conclusions about the impact of technogenic objects on the environment, it is necessary not only to study soils but also to study all other components of the landscape. Soil TPI is an indicator that takes into account the combination of various pollutants in the soil, including the presence of toxic metals, chemicals, radionuclides, etc. (Trigub & Domuschi, 2023). This indicator provides a general assessment of the degree of soil pollution and allows for a comparative analysis between different territories. It is measured in units that correspond to certain standards or pollution norms.

According to the obtained results, the construction of a design geoinformation map for environmental monitoring of the Ivano-Frankivsk urban community should be based on the following principles. Data collection: the first stage is the collection of relevant data on the state of the environment, such as the concentration of various pollutants in soils, water, air, etc. This data can be obtained from various sources, including laboratory measurements, satellite imagery, monitoring sensors, etc. After data collection, geoinformation analysis is carried out, which includes data processing and analysis using GIS technologies. This may involve creating digital maps, using analytical methods to detect patterns and trends in pollution, identifying pollution hotspots, and so on. Visualisation of results: one of the main aspects of a design geoinformation map is the visualisation of the obtained results. This can be done by creating thematic maps, graphs, and charts that illustrate the distribution of pollutants, their concentration, trends of change, etc. Interpretation and analysis: the final stage is the interpretation and analysis of the obtained results to formulate conclusions and recommendations. This may include identifying potential risks to human health and ecosystems, establishing the causes of pollution, assessing the effectiveness of monitoring measures, and increasing public environmental awareness.

Overall, the construction of a design geoinformation map for environmental monitoring (Fig. 9) is based on the integration of GIS data, its analysis, and visualisation to obtain a comprehensive understanding of the state of the environment and develop strategies for conservation and environmental protection. According to the specified functions for administrative management bodies of the Ivano-Frankivsk UATC, the geoinformation map of environmental monitoring should include the following interrelated structural elements: databases and data banks of element concentrations in all landscape components; forecasting the spread of chemical elements in the natural-anthropogenic system based on calculation-graphic methods; determination of MPC zones of harmful substances in the studied area; interpolation of pollution and modelling the distribution of pollution; reporting the results of the conducted work to determine the environmental status of the study area and measures for its improvement; social development programmes aimed at increasing the environmental safety of the population of the area. These elements interact with each other, providing the necessary information for making management decisions regarding the environmental safety of the population. The geoinformation map should reflect these functions in the corresponding layers and combine them for convenient analysis and use by management bodies.

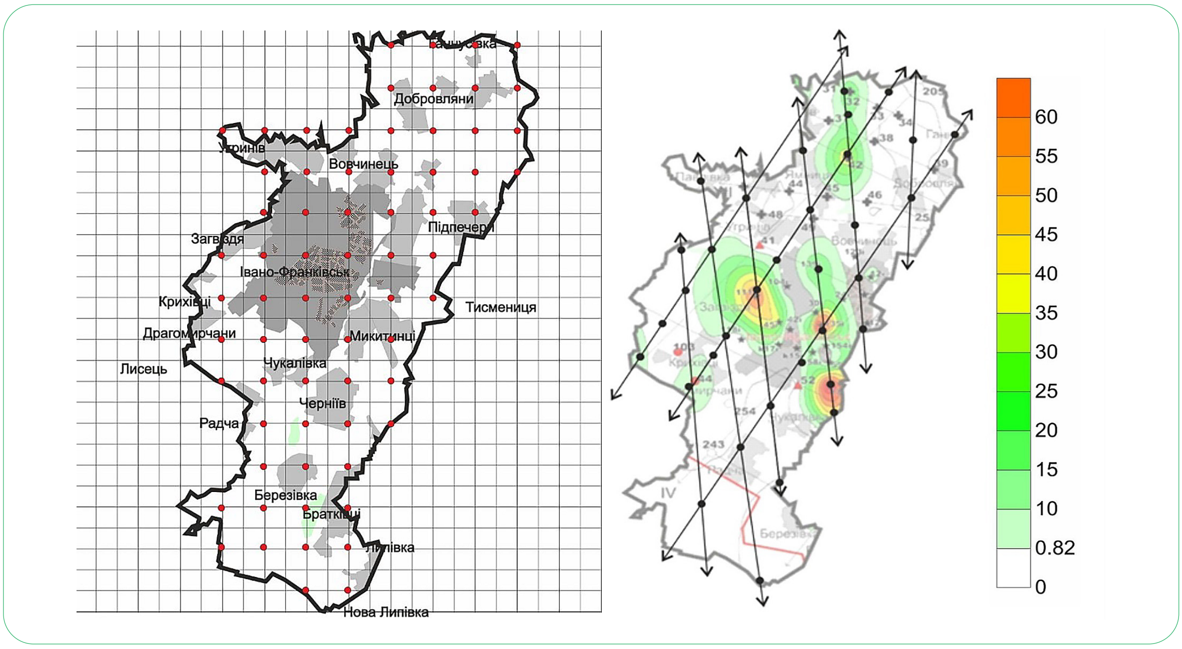

Figure 9. Design map of environmental monitoring of the territory (parallel routes and loops)
Source: created by the author

A GIS for environmental monitoring can be effectively organised by dividing it into problem-oriented blocks and thematic layers of information according to their functional purpose. The geoinformation support of such a system should contain the following thematic layers of information. General physical-geographical information, which includes hydrological networks and water bodies; settlements; administrative boundaries; relief; characteristics of the phytosphere; communication routes (land and underground transportation highways, heat pipelines); power transmission lines, etc. Sources of negative environmental impact, such as discharges and emissions; and household waste. Geo-ecological polygons, which include: sampling points and research routes. Natural protected areas, which may include: water protection zones and historical monuments, etc. Environmental characteristics, containing layers of pollution by various chemical elements in all landscape components: atmosphere; hydrosphere; lithosphere; geomorphosphere; geophysics sphere; pedosphere. Health protection and socio-domestic conditions, including demography and disease incidence of the population, etc. Categorising information in this way ensures convenient access to data and their analysis for making effective management decisions regarding environmental safety.

Collecting information about the state of the soil cover is an important component of the environmental monitoring system. For this purpose, laboratory analyses are used, or special automatic devices that can check the level of harmful substances. After obtaining the results, they are entered into a Microsoft Excel database for further analysis and use in solving environmental problems. The database containing information about the soil cover includes data on environmental pollution. The data bank should reflect the geographical coordinates of sampling points, stationary posts, or the locations of mobile laboratories, as well as the time of measurements and physical-geographical references. This database includes data on production and processing facilities, such as enterprises, workshops, as well as information on emissions or discharges. Planning databases on soil cover or other monitoring objects is carried out in accordance with the above principles (Table 2).

Thematic layers in GIS related to the analysis of major pollution sources should be represented using appropriate cartographic material. Databases containing information about the object under study, along with the corresponding cartographic material, allow obtaining answers to the following queries: the physical-geographical characteristics of the study area (location, length of communication routes, the area of the catchment basin, altitude, etc.); which area is polluted with harmful substances; which zones exceed MPC levels; which zones do not exceed background indicators (natural contents, clean unpolluted areas); which objects emit specific harmful substances and which harmful substances are distributed in the study area can be determined using databases with corresponding cartographic material; which enterprises negatively impact the environmental condition. By overlaying thematic layers in GIS, it is possible to conclude the source of environmental hazards to make appropriate management decisions. For example, by overlaying concentrations of Cd, Zn, Ni, or the TPI on physico-geographical thematic layers, a map of the current ecological situation of the study area is created.

Discussion

Within the framework of environmental monitoring of the Ivano-Frankivsk urban community and the analysis of geochemical mapping, it is necessary to emphasise the significant contribution of a number of recent studies that consider the main tools of geochemical mapping. In particular, J. Wang *et al.* (2024) in their article on mapping geochemical anomalies taking into account the instability of mineralisation-related element associations, consider the fundamental tools of geochemical mapping for studying the distribution and behaviour of economically significant elements and providing useful information about geological processes. However, the quantitative assessment of uncertainty associated with geochemical mapping has recently become a subject of general concern. This study proposes a procedure that involves defining homogeneous clusters, recognising element associations for each cluster, and identifying geochemical anomalies to account for the uncertainty of element associations in geochemical mapping. In the current study, GIS and pollution interpolation have indeed become key tools for analysing and visualising environmental data. The use of GIS allows not only to collection and analysis of pollution data but also to integration of it into a spatial context, which contributes to a better understanding of the distribution of pollution in the environment.

B. Zhou & X. Li (2021) developed software and wrote an original project. The project aims to understand the situation of agricultural environmental pollution by chemical pesticides based on GIS, understand the situation of agricultural crops and the main situation of the use of agricultural crops, and provide instructions and recommendations for monitoring environmental pollution. In their research, T. Kozlowski *et al.* (2023) developed information technology projects aimed at developing intelligent environmental monitoring systems. These projects are based on standardised requirements for software development defined in ISO 25010. These requirements are used as a primary tool for creating business-oriented "smart" environmental monitoring systems. The research methods in these articles describe artificial intelligence algorithms and models used for data analysis and the development of digital solutions. The authors of the current study propose solving these problems through monitoring and sampling the quality of all environmental components and analysing pollutants using statistical analysis, data collection, and processing to create cartographic material. In other words, it is proposed to study all components of the natural and anthropogenic environment. In previous studies, D. Zorin (2022) developed electronic cartographic GIS models of the environmental state of the Dniester Canyon, which describe the assessment of all environmental components.

In the research of L. Arkhypova *et al.* (2021), the idea of expanding the potential use of renewable energy sources in the Carpathian region by creating a set of maps in the GIS MapInfo for each type of renewable energy is considered. For comparison, this article describes obtaining accurate interpolations of elements; the maps should use characteristic intervals, rather than arbitrarily from polygon to polygon. This will allow for obtaining more accurate and representative results, as it will be able to take into account variations in concentrations within defined ranges. Only such an approach to constructing cartographic material will convey the nature of the element's distribution in the environment, according to the methodology described in this article above. Also, data on the state of vegetation and water resources in different territories can be obtained using modern technologies such as studying satellite images of degraded areas, GIS, and the differential vegetation index, the normalised differential humidity index, and the differential water index. A. Dzyba & V. Kyriienko (2024) assessed biomass growth in the Kakhovka Reservoir using these methods. A strong correlation between plant growth rates and their moisture availability was revealed by studying the relationships between indicators; a comparable study was conducted by M. Kutia *et al.* (2023) in Changsha, China.

Interpolation of data on soil or air pollution allows obtaining an estimate of the pollution distribution over the entire study area, even in places where samples were not collected. The application of interpolation methods, such as Kriging, can provide accurate results that are useful for making decisions on environmental protection and developing pollution reduction strategies. However, it is important to remember the limitations of interpolation methods, such as dependence on the location of the original data and the possibility of artefacts occurring as a result. In addition, the accuracy of interpolation can depend on the uniformity of the location of data points and the consideration of various factors that affect the distribution of pollution. In the future, for further development of research in this area, it may be useful to combine GIS interpolation methods with other analytical and statistical methods to obtain more accurate and reliable results.

The research of V. Trysnyuk & Ye. Nahornyy (2024) highlights the importance of using information technologies, particularly interpolation methods, for processing radioactive contamination data. Taking errors into account in measurements and utilising interpolation methods allow for accurately describing fields of radiation contamination in the area. This helps to ensure effective monitoring and protection of the population after nuclear events, contributing to the preservation of public health and safety. In the study by I. Krasovska *et al.* (2020), the ecological state of the border territories of Poland and Ukraine is considered, focusing on water pollution in rivers and its potential negative consequences. Through a comprehensive analysis, the main environmental factors have been identified. The study supports the necessity of an interdisciplinary approach that considers the diversity of monitoring data and applies modelling to predict pollution trends in river systems, facilitating timely interventions to prevent adverse ecological impacts.

The relevance of using GIS in environmental monitoring lies in its ability to provide a comprehensive analysis and visualisation of environmental data on a geographic map. GIS allows the integration of a variety of information about pollution, natural resources, terrain, transportation networks, and other environmental parameters, which allows the making of objective conclusions about the environmental state of a territory. In addition, GIS contributes to more effective monitoring of changes in the environment and the development of strategies for preserving natural resources and preventing pollution. The use of GIS in environmental monitoring is a key tool for making informed decisions in the field of environmental protection and sustainable development. It is advisable to further integrate into the GIS monitoring system modules for monitoring all components of the environment, their spatial distribution, a module for forecasting potential landscape changes, a module for remote sensing of the Earth, and based on relief isolines analysis, develop 3D models of the studied territory. Thus, the application of GIS provides the opportunity to create a unified information space for territorial management services, which contributes to increasing the efficiency and convenience of data processing and analysis (Adamenko *et al.*, 2022).

Comparing older technologies with modern innovations, including open cloud solutions that allow for the analysis and visualisation of large volumes of heterogeneous geodata and time series of observations of dynamic parameters, as shown by L. Davybida *et al.* (2021), it can be seen that the use of GIS in environmental monitoring is becoming a key factor in solving current problems. By analysing the methods and principles of GIS construction, one can observe significant advantages in creating cartographic models, analysing the distribution of chemical elements, and making management decisions for environmental safety. According to E.D. Kuzmenko *et al.* (2020), the use of GIS allows for the collection, processing, and analysis of large volumes of data, which contributes to eliminating environmental problems and improving the quality of the environment.

The combination of GIS and Earth remote sensing is the toolkit that allows solving most environmental monitoring tasks. This confirms that the development and implementation of new technologies in the field of ecology is an important step towards the sustainable development of our society. Given the relevance and importance of this topic, this article considers the possibilities of using GIS for environmental monitoring at the local level, in particular for assessing the condition of the soil cover in the Ivano-Frankivsk urban community. The authors analyse various monitoring methods, including remote and chemical methods, and propose options for building an environmental monitoring system based on GIS technologies.

Conclusions

As a result of the conducted research, significant results were obtained indicating the state of the environment and soil cover in the Ivano-Frankivsk Region. The analysis showed that the most common cultural soil layer in Tysmenytsia and Ivano-Frankivsk is the one containing the remnants of building materials and other human waste. It was found that these cultural soil layers have increased degradation, caused by excessive pollution with various types of waste and toxic substances. A particular problem is the insufficient ability of these soils to remove toxic chemical elements, leading to their accumulation and spread. The results of the analysis of 117 soil samples showed that the soils of urbanised areas are subject to the negative impact of the same factors as urban air and hydrosphere. Such conclusions emphasise the need to create and implement an effective environmental monitoring system to identify and manage environmental problems. Such a system would enable the development and implementation of informed measures to conserve the environment.

One of the key tasks is the implementation of an environmental monitoring system using GIS software such as MapInfo and Surfer. This will allow for systematic tracking of changes and trends in the distribution of chemical elements and other environmental parameters and timely response to potential environmental threats. In addition, the research opens up opportunities for the introduction of new methods and technologies, such as GPS and GIS software, in the field of environmental monitoring. This will contribute to increasing the accuracy and efficiency of monitoring measures aimed at preserving the environment. The study paves the way for further research in the field of environmental monitoring and the application of GIS technologies to solve complex environmental problems. It also highlights the importance of cooperation between research institutions, local authorities, and the public to create integrated approaches to environmental protection and sustainable urban development.

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Conflict of Interest

None.

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Визначення екологічного стану ґрунтового покриву та проектування екологічного моніторингу Івано-Франківської міської громади

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Анотація. Через зростання техногенного навантаження на довкілля необхідно визначити ступінь впливу промислового виробництва на навколишнє середовище. Проведення екологічного моніторингу Івано-Франківської міської об'єднаної територіальної громади дасть можливість подальшої екологічної оцінки та прогнозування стану довкілля досліджуваної території. Мета роботи – оцінити стан ґрунтового покриву Івано-Франківської міської громади та її околиць, визначити актуальність використання геоінформаційних систем (ГІС) в екологічному моніторингу. У дослідженні використовувалися: статистичний метод для збору та аналізу баз даних екологічної ситуації зі забруднення компонентів довкілля; ГІС картографія для виявлення та відображення поширення забруднюючих компонентів за допомогою інтерполяції методом Kriging. Проведено детальний аналіз різних методів моніторингу стану навколишнього середовища, включаючи дистанційні та хімічні методи. Це дозволило визначити найбільш ефективні підходи для збору та обробки екологічних даних. Розглянуто важливі аспекти створення системи екологічного моніторингу для відстеження стану навколишнього середовища. На основі зібраних даних створено карти, що відображають розповсюдження хімічних елементів на території Івано-Франківської міської об'єднаної територіальної громади. Ці карти є важливим інструментом для візуалізації та аналізу екологічного стану ґрунтів. Запропоновано варіант побудови системи екологічного моніторингу та розроблено проектну картографічну модель. Це дозволить більш ефективно здійснювати екологічний моніторинг та планувати заходи щодо покращення екологічного стану території. Застосування програмного забезпечення MapInfo та Surfer дозволило провести детальний аналіз навколишнього середовища та створити геоінформаційну систему екологічного моніторингу для Івано-Франківської міської громади. Результати дослідження мають значне практичне значення для різних сфер екологічного менеджменту та планування, зокрема для проведення подальшого екологічного моніторингу, для сфер державного та місцевого екологічного управління, громадських ініціатив та освітніх програм

Ключові слова: геоінформаційні системи; картографія; техногенний вплив; польові дослідження; коефіцієнт концентрації