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Screening of natural (^{238}U and ^{232}Th series, ^{40}K) and technogenic (^{137}Cs) radionuclides, as well as heavy metals in river sediments in Transcarpathia

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Abstract. Bottom sediments are an important indicator of the state of rivers, as they are capable of accumulating natural and technogenic substances, reflecting background geochemical features and anthropogenic load. The aim of the study was to analyse the content of natural and technogenic radionuclides and heavy metals in the rivers of Transcarpathia to identify patterns in their distribution and further assess bioaccumulation in the "bottom sediments – ichthyofauna" system. To achieve this goal, γ-spectrometric analysis was performed on the "ORTEC" complex and X-ray fluorescence determination of metals was performed using the "Elvax Pro" analyser. Samples were collected in 2023-2024 from eight points within the Uzh, Latorica, Borzhava, and Tysa rivers. The results showed spatial variability caused by a combination of geological, morphological and anthropogenic factors. The total activity of natural radionuclides (U- and Th- series) was found to be within the range of 340-534 Bq/kg, with the highest values found in the areas of Uzhhorod, Vylok, and Chop. The highest activity of the natural radionuclide K-40 (522-533 Bq/kg) was recorded in areas with the presence of potassium minerals and agricultural load – Pidpolozzia, Kolchyno and Chop. Cs-137 had low activity (2.9-7.0 Bq/kg), with a local increase in fine-grained silt. The geochemical index Th/U (0.63-1) showed the mineralogical diversity of sediments. Analysis of heavy metal content revealed spatial differences: Zn concentrations ranged from 1.4 to 89.9 mg/kg, Pb from 4.4 to 8.9 mg/kg, Cu from 3.9 to 9.7 mg/kg, Ni from 5.1 to 8.3 mg/kg, and Cr – from 6.3 to 13.0 mg/kg. The highest values of elements were found in urban areas (Uzhhorod, Chop), and the lowest – in mountainous areas with minimal anthropogenic impact. The concentrations of heavy metals did not exceed environmental standards, but local maxima indicated potential pollution. The practical significance of this study lies in the use of its results for

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environmental monitoring, predicting the migration of elements and assessing their bioaccumulation in aquatic food chains

Keywords: geochemical monitoring; background radiation; river sediments; toxic elements; river ecosystems

INTRODUCTION

Bottom sediments act as an indicator for the accumulation of hazardous substances in riverine ecosystems, as they have a high sorption capacity to accumulate both natural and technogenic substances. They can reflect the geochemical characteristics of a territory and the general environmental conditions, which makes it possible to assess the consequences of anthropogenic pressure on aquatic ecosystems. Analysing the composition of bottom sediments provides a generalised overview of the state of water bodies and helps to identify areas that require heightened attention within a monitoring framework. In the Transcarpathian region, such a study is particularly relevant because the rivers in the area flow through various landscapes and geological zones. This, in turn, allows for an analysis of pollutant concentration levels in different sections of the rivers. Special attention should be paid to radionuclides and heavy metals when assessing the state of the region's riverine ecosystems. A comprehensive analysis of these components makes it possible to characterise the ecological stability of riverine ecosystems and to identify potential sources of pollution or local foci of increased anthropogenic impact.

An analysis of modern scientific research confirms the relevance of studying the processes of radionuclide and heavy metal accumulation in bottom sediments across different geographical regions. These studies demonstrate that the activity of natural and technogenic radionuclides in bottom sediments depends on geomorphological, hydrological, and anthropogenic factors. In a study by R. Federico *et al.* (2020), the high mobility of Cs-137 in fine-grained sediments and its effective incorporation into trophic chains were noted, which allows for the assessment of potential risks of radionuclide transfer to organisms in riverine biocenoses. The work of T. Abere *et al.* (2025) showed that the activity of natural and technogenic radionuclides in bottom sediments varies significantly depending on the geomorphological and hydrological conditions of the rivers. The authors noted that the flow velocity, seasonal water level changes, and the nature of the bottom cover affect local radionuclide concentrations, which is especially important for assessing high-risk contamination zones. Ukrainian researchers O. Symkanych *et al.* (2024) emphasised the significance of combining geological and morphological factors with anthropogenic influence in forming the spatial distribution of radionuclides in the Transcarpathian region, while the work of N.I. Svatiuk *et al.* (2022) noted that systematic radioecological monitoring allows for the assessment of the intensity of human activity and its consequences for riverine ecosystems. Additionally, these studies demonstrate that a combined analysis of natural and technogenic radionuclides makes it possible to identify general trends in the impact of anthropogenic factors on the riverine ecosystem. The research by O. Hromyk *et al.* (2020) proved that the level of background radiation in bottom sediments depends on the geological characteristics of the area, and comprehensive radioecological monitoring (particularly concerning natural radionuclides) helps to identify potential sources of pollution. In the work of I. Cimbolakova *et al.* (2020), it was shown that heavy metals, particularly the mobile forms of Zn, Cu, Pb, and Ni, are characterised by high toxicity and the ability to be redistributed and accumulated in the biotic components of aquatic ecosystems, which determines their ecological danger. R.N. Khalef *et al.* (2022) and R. Osae *et al.* (2023) showed that solubility and the ability to form complex compounds determine the migration of heavy metals in the natural environment. These studies highlight the importance of a comprehensive approach to analysing heavy metal content, as the simultaneous determination of their concentrations and spatial distribution allows for the assessment of their impact on biota and the ecological stability of riverine ecosystems. At the same time, they demonstrate that the interaction of heavy metals with bottom sediments is determined not only by the chemical properties of the metals but also by the structural characteristics of the sediments, which affects their mobility and availability to living organisms.

The aim of the study was to conduct a screening analysis of the content of natural and technogenic radionuclides, as well as heavy metals in the bottom sediments of the main rivers of Transcarpathia (Uzh, Latorica, Borzhava, and Tysa), determining the characteristics of their distribution for monitoring the state of river ecosystems in the region and further assessing the bioaccumulation of pollutants in the "bottom sediments – ichthyofauna" system. To achieve this goal, the following tasks were set: selection and preparation of bottom sediment samples with subsequent determination of the specific activity of radionuclides using γ-spectrometry; determination of heavy metal concentrations by X-ray fluorescence analysis; assessment of the spatial distribution of the specific activity of radionuclides and the concentration of heavy metals in different sections of the rivers of Transcarpathia. The novelty of the work lies in the comprehensive screening of natural and technogenic radionuclides together with heavy metals in the bottom sediments of the region's rivers, and the identification of patterns in their spatial distribution.

MATERIALS AND METHODS

For the analysis, three bottom sediment samples were taken at each of the eight control points: Uzhhorod, Pidpolozzia, Kolchyno, Dovhe, Rakhiv, Vylok, Tiachiv, and Chop (within the main rivers of Transcarpathia: Uzh, Latorica, Borzhava, and Tysa) (Fig. 1). For each point, an average sample was prepared from the three collected probes. Some of the samples were collected in 2023, and the rest in 2024, during the spring-autumn period of both years, depending on the accessibility of the points and hydrological conditions. The results are presented as averages for the entire aforementioned period, which allowed for a general understanding of the spatial distribution of natural and technogenic radionuclides and heavy metals in the bottom sediments. Sampling, transportation, and storage were carried out according to standard methods in compliance with DSTU ISO 5667-12-2001 (2002) and DSTU ISO 5667-15:2007 (2011). Bottom sediment samples, weighing over 1500 g, were collected manually from a depth of approximately 5-15 cm. They were transported and stored in polyethylene bags with a label indicating the collection date, sample number, and information about the sampling location. The samples were dried at room temperature (18-25°C) until they reached a constant mass. This approach helped to avoid the loss of volatile components and preserve the total content of heavy metals. The dried samples were then ground by hand to a fine, homogeneous powder. After grinding, foreign residues (plant roots, stones, glass, etc.) were removed from the samples, and then the sample was sieved to a homogeneous mass with a fraction size of up to 100 μm.

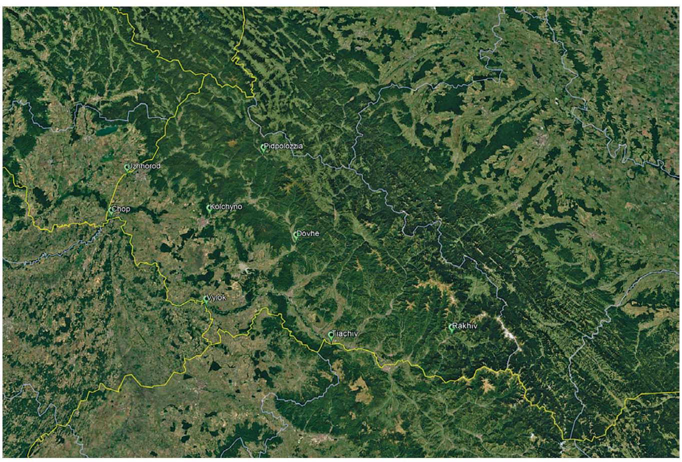

Figure 1. Location of bottom sediment sampling points in the Transcarpathian region
Source: developed by the authors based on Google Earth (n.d.)

Radiological studies were conducted at the Department of Photon-Nuclear Processes of the Institute of Electronic Physics of the National Academy of Sciences of Ukraine (Uzhhorod). The prepared silt samples, weighing 1-1.5 kg, were placed in a Marinelli beaker for radiospectroscopic analysis. The specific activity of gamma-active nuclides (U-238 (Pb-214, Bi-214, Ra-226), Th-232 (Pb-212, Bi-212, Ac-229, Tl-208), K-40, Cs-137) in the bottom sediments was determined using an "ORTEC" semiconductor γ-spectrometer system with a 150 cm³ HPGe-detector. During the measurements, the energy scale drift, resolution, and registration efficiency of the spectrometer were constantly monitored using standard Co-57 and Co-60 point gamma-active sources. The territory was mapped using the "QGIS 3.40.1-Bratislava" software, referenced to the coordinates of the bottom sediment sampling points.

The heavy metal content was determined using an "ElvaX Pro" X-ray fluorescence analyser (Ukraine), at the Transcarpathian Research Forensic Expert Service Centre of the Ministry of Internal Affairs of Ukraine. To assess the accuracy of this method, the Fe content was additionally determined in the samples using spectrocolorimetry. The results obtained by this method were used as a reference against which the relative concentrations of other elements, measured with the X-ray fluorescence analyser, were recalculated. The discrepancy between the methods did not exceed 10%, which is consistent with the stated error. The reproducibility of the results was confirmed by three measurements of one sample, with a difference of no more than 5-7%. The prepared samples were poured into a standard analytical cuvette of the instrument as a dense layer 3-5 mm thick, without additional binders or pressing. The analysis was performed in a vacuum mode, which improves the detection of light elements by reducing the absorption of X-ray radiation by atmospheric gases. Two operating modes were used: one for light elements and one for elements of medium and high atomic mass. In the first mode, the tube voltage was 12 kV, the current was 100 μA, and the pulse rate was stabilised at 300,000 pulses per second with a permissible deviation of ±10%. The second mode had the following settings: tube voltage – 35 kV, current – 200 μA, and the pulse registration rate was stabilised at 450,000 pulses per second with a permissible deviation of ±10%. The exposure time for each mode was 100-200 seconds. The presented heavy metal concentrations include a calculated error of ±10%, which accounts for the use of the non-pressing sample preparation method and the specifics of drying at room temperature. Furthermore, the stabilisation of the instrument's signal ensures the reproducibility of the measurements, which is confirmed by three independent analyses of the same sample. Spectral data processing was carried out using the instrument's integrated "Elvatech" software with an automatic peak identification and concentration calculation function (in percentages). Additional calculations were performed using Exel software to convert the percentage concentrations to mg/kg of dry mass. A conversion factor was used to convert the concentrations from percentage content to mg/kg, determined from the reference value for iron:

$$k = \frac{C_{Fe}}{\omega_{Fe}}, \tag{1}$$

where k – the conversion factor, C_{Fe} – the Fe concentration in mg/kg determined by spectrocolorimetry, ω_{Fe} – the Fe content in the sample expressed as a percentage.

The resulting coefficient characterises the correspondence between the percentage and mass expression of the iron concentration of each sample. For other elements, the concentration in mg/kg was calculated using the formula:

$$C_x = \omega_x \times k, \tag{2}$$

where C_x – the concentration of element x in the sample in mg/kg, ω_x – the content of element x in %, k – the conversion factor (mg/kg per 1%).

RESULTS AND DISCUSSION

The research data showed that the content of radionuclides and heavy metals in the bottom sediments of Transcarpathian rivers is characterised by significant spatial variability. The specific activities of natural (U-, Th-series and K-40) and technogenic (Cs-137) radionuclides showed a clear dependence on the geological features of the region. The obtained specific activity values indicate not only the influence of geological conditions (in particular, the type and mineralogical composition of rocks, granulometric composition of sediments), but also anthropogenic factors (such as the influence of urbanised areas, probable agricultural load). In the lowland areas of the region, elevated levels of natural and technogenic isotopes were recorded, while in mountainous areas, lower values were observed due to the predominance of coarse-grained fractions and high flow rates. Concentrations of heavy metals such as Zn, Pb, Cu, Ni and Cr reflect a combination of natural biochemical background and local sources of pollution. The analysis showed that fine-grained sediments in the lower reaches of rivers accumulate metals better due to the high absorption capacity of clay fractions and organic matter, while in fast-flowing mountainous parts of rivers with a predominance of coarse-grained material, metal accumulation is significantly lower. Data on the content of radionuclides K-40, Cs-137, natural series U-237 and Th-232 are given in Table 1.

Table 1. Results of the study of the specific activity of gamma-active radionuclides in bottom sediments of rivers in Transcarpathia

River sections	Specific activity of gamma-active radionuclides, Bq/kg										ΣA, Bq/kg	ΣTh232/ΣU237
	K40	Cs137	U237 Series			Th232 Series						
			Ra226	Pb214	Bi214	Pb212	Ac228	Ac229	Bi212	Tl208		
Uzh River												
Uzhhorod	494.4 ±49.4	5.1 ±0.5	133.6 ±13.4	79.4 ±7.9	84.0 ±8.4	52.9 ±5.3	70.2 ±7.0	44.1 ±4.4	53.9 ±5.4	15.8 ±1.6	533.9	0.8
Latorica River												
Pidpolozzia	522.5 ±52.3	4.3 ±0.4	55.0 ±5.5	100.3 ±10.0	104.6 ±10.5	48.2 ±4.8	61.2 ±6.1	39.5 ±3.9	39.3 ±3.9	15.7 ±1.6	463.7	0.8
Kolchyno	527.0 ±52.7	4.7 ±0.5	89.5 ±8.9	60.1 ±6.0	54.6 ±5.5	51.6 ±5.2	48.5 ±4.9	42.9 ±4.3	42.6 ±4.3	13.8 ±1.4	403.4	1.0
Borzhava River												
Dovhe	474.4 ±47.4	7.0 ±0.7	85.3 ±8.5	87.2 ±8.7	80.6 ±8.1	41.3 ±4.1	52.4 ±5.2	36.7 ±3.7	22.3 ±2.2	14.8 ±1.5	420.6	0.7
Tysa River												
Rakhiv	431.2 ±43.1	2.9 ±0.3	88.9 ±8.9	54.4 ±5.4	72.6 ±7.3	33.5 ±3.4	36.7 ±3.7	27.1 ±2.7	29.3 ±2.9	10.3 ±1.0	352.7	0.6
Tiachiv	418.4 ±41.8	3.4 ±0.3	61.8 ±6.2	6.0 ±6.3	68.0 ±6.8	32.1 ±3.2	33.9 ±3.4	31.7 ±3.2	39.9 ±4.0	10.0 ±1.0	340.4	0.8
Vylok	506.4 ±50.7	4.8 ±0.5	130.1 ±13.0	69.8 ±7.0	66.0 ±6.6	45.6 ±4.6	40.8 ±4.1	42.2 ±4.2	82.9 ±8.3	14.9 ±1.5	492.3	0.9
Chop	533.1 ±53.3	4.2 ±0.4	130.4 ±13.0	62.8 ±6.3	69.6 ±7.0	45.9 ±4.6	49.3 ±4.9	43.9 ±4.4	55.6 ±5.6	13.6 ±1.4	471.1	0.8
Average Values												
	488.6	4.6	96.8	72.1	75.0	43.9	49.1	38.5	45.7	13.6	434.8 ±43.5	0.8 ±0.1

Note: ΣA – total specific activity of all natural radionuclides studied, excluding K-40; ΣTh-232/ΣU-238 – the ratio of the total specific activity of isotopes from the thorium and uranium series, which was used as an indicator of the mineralogical properties of the bottom sediments
Source: developed by the authors

The results presented in Table 1 show a summary of the quantitative indicators of the main isotopes of the U- and Th-series, as well as the isotopes of natural K-40 and technogenic Cs-137 for different sections of the studied rivers in the Transcarpathian region. The data in the table show that the specific activities of natural radionuclides vary significantly depending on the section of the river. The highest values of the total specific activity of all studied natural radionuclides, except for K-40 (ΣA), were recorded in the area of Uzhhorod and near the village of Vylok, while the lowest values were recorded in Tiachiv and Rakhiv. K-40 showed higher activity in the lowland areas of the region. The specific activity of Cs-137, as a technogenic isotope, is generally low, but its level is elevated in deposits with a fine-grained fraction (e.g., Dovhe and Uzhhorod) (Table 1). Particular attention should be paid to the ratio of the total specific activity of isotopes of the thorium and uranium series (ΣTh232/ΣU237), which can be used as a marker of the mineralogical characteristics of deposits. The data in Table 1 allow to identify key spatial patterns, which are confirmed by the following figures in this section. The values of the total specific activity of natural radionuclides (U- and Th-series, except for K-40), illustrated in Figure 2, ranged from 340 to 534 Bq/kg.

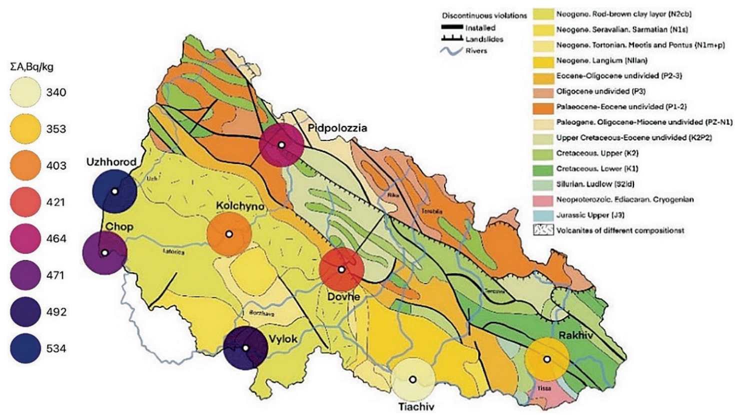

Figure 2. Visualisation of the spatial distribution of the total activity of natural radionuclides (ΣA) in bottom sediments of rivers in Transcarpathia, Bq/kg
Source: developed by the authors based on Geomap Land (n.d.)

Figure 2 shows that the maximum specific activities of natural radionuclides (U- and Th-series, except K-40) were recorded in Uzhhorod, Vylok and Chop. This is due to a combination of geological factors (the presence of sedimentary and volcanic rocks) and anthropogenic influences in urbanised areas. Similar patterns were described by M. Cabral-Lares *et al*. (2022), who found that in areas with active anthropogenic load and different geological formations, the accumulation of elements in bottom sediments increases. Also, in fine-grained silt sediments in the lowland part of the region, minerals and organic matter actively sorb uranium and thorium, which is consistent with the conclusions of E. Juranova *et al*. (2020). A similar effect is confirmed in the works of K.S. Patel *et al.* (2023), where fine fractions and organic matter were the main accumulators of U and Th for various aquatic and sedimentary ecosystems. Significantly lower values were found in mountainous areas (Tiachiv, Rakhiv), where coarse-grained fractions with a lower capacity to accumulate uranium and thorium prevail in fast-flowing streams. These results coincide with the conclusions of Y. Zou *et al*. (2025), who studied the mechanisms of accumulation of these elements in marine bottom sediments. Also, high flow velocity reduces the possibility of accumulating organic matter, which can be an active medium for uranium sorption. Figure 3 shows the specific activity of K-40 in selected bottom sediment samples.

Figure 3 shows that the specific activity of K-40 in the region ranged from 418 to 533 Bq/kg. The highest values of specific activity of K-40 were recorded in Chop, Pidpolozzia, and Kolchyno, which are located on alluvial terraces within volcanogenic-sedimentary and Neogene formations that are naturally enriched with potassium. This pattern is consistent with the geological structure of the area, as Chop is located in a zone of Neogene alluvial deposits on the flat part of Transcarpathia. The high K-40 content here can also be explained by the accumulation of fine-grained fractions that actively bind potassium, as well as the probable influence of agricultural load – in particular, the use of potassium-containing fertilisers in lowland areas of rivers with agricultural significance upstream. Kolchyno is located directly on the territory of the Vyhorlat-Hutin Ridge, which forms the inner part of the Eastern Carpathians and is characterised by the prevalence of rocks with a high content of potassium minerals. Similar conclusions are presented in the work of S. Gönczy *et al*. (2020), which analyses the geological conditions of the North-Eastern Carpathians and points to their high mineralogical diversity.

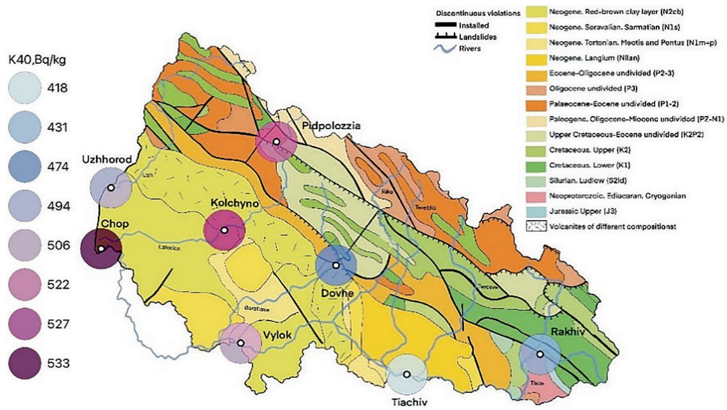

Figure 3. Visualisation of the spatial distribution of specific K-40 activity in bottom sediments of rivers in Transcarpathia, Bq/kg
Source: developed by the authors based on Geomap Land (n.d.)

The role of alluvial deposits and their ability to accumulate potassium is confirmed in a study by J.A. McIntosh *et al*. (2023), who found a significant content of potassium minerals in clay fractions. The level of specific activity of K-40 in Pidpolozzia is explained by the mineralogical composition of sedimentary rocks containing illite, muscovite and feldspars, which have a high potassium content and high adsorption capacity, which is consistent with the conclusions of V.V. Reinoso Carbonell *et al*. (2022). The lowest values are observed in Tiachiv, located in an area dominated by sandy-gravel material of mountain rivers with a relatively high flow velocity, due to which bottom sediments in this area are less capable of accumulating K-40. The same conclusions can be found in the study by H.E. Heldal *et al*. (2021). The data on the ratio of the total specific activity of the thorium series to the total specific activity of the uranium series (ΣTh-232/ΣU-238) in the studied areas of the Transcarpathian region are illustrated in Figure 4.

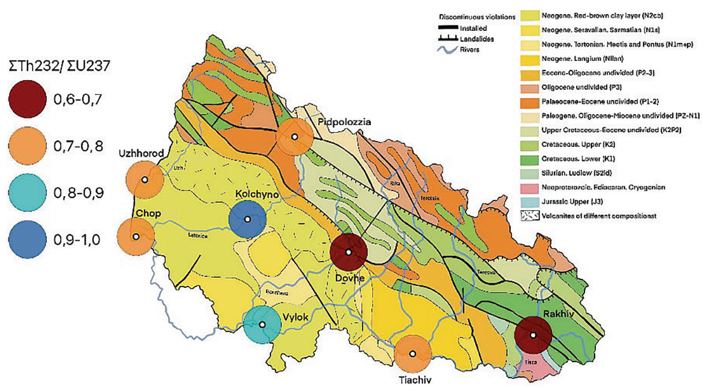

Figure 4. Visualisation of the ratio of total specific activity Th/U in bottom sediments of rivers in Transcarpathia
Source: developed by the authors based on Geomap Land (n.d.)

The Th/U ratio is an important indicator of the mineralogical diversity of bottom sediments in the region. Figure 4 shows that the lowest values (<0.7) were recorded in Dovhe and Rakhiv. In a study by L. Cao *et al*. (2021), this pattern is associated with the peculiarities of the geological structure, in particular the presence of Neogene and volcanogenic formations. In contrast, the highest values of the ratio (0.9-1.0) are characteristic of the southwestern part of the region, particularly in the Vylok and Kolchyno areas, where more consolidated Neogene sedimentary rocks dominate. At the same time, in the Uzhhorod and Chop areas, despite the presence of Neogene deposits, the ratio is lower (0.8), which can be explained by more active hydrodynamic processes. Figure 5 shows the distribution of technogenic Cs-137 in the bottom sediments of the rivers of Transcarpathia.

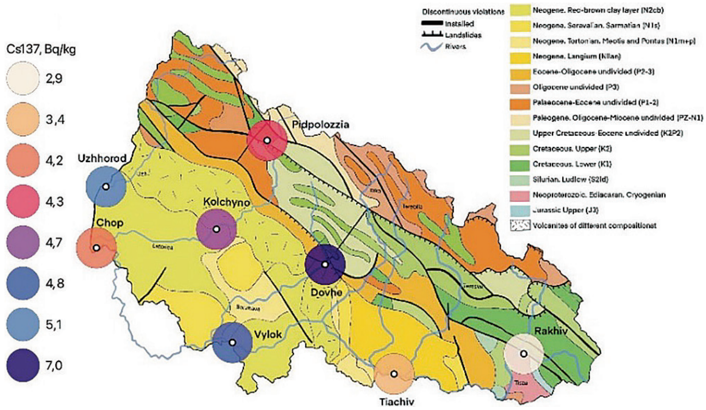

Figure 5. Visualisation of the spatial distribution of specific Cs-137 activity in river sediments in Transcarpathia, Bq/kg

Source: developed by the authors based on Geomap Land (n.d.)

As can be seen in Figure 5, the specific activity level of Cs-137 is generally low. The highest values were found in Dovhe, Uzhhorod, Vylok, and Kolchyno. Cesium is most effectively sorbed by clays and organic matter, especially in fine-grained silt. Similar patterns were noted by E.O. Akuo-ko *et al*. (2025) on the example of the Ghana coast: Cs-137 concentrations were highest in fine-grained and organically enriched sediments. In places with slow currents, such as in Dovhe, conditions are created for the accumulation and sedimentation of caesium. Similar results are presented in a study by G. Mouri (2020), which showed that Cs-137 was actively sorbed in areas with slow currents. Accordingly, the fast flow of mountain rivers does not contribute to sedimentation, and the organic content at these points is significantly lower. The concentrations of heavy metals in bottom sediments showed significant spatial variability. To convert the concentrations from percentage content to mg/kg, formulas 1 and 2 given in the "Materials and Methods" section were used. In particular, the conversion factor for Fe (formula 1) was first calculated, after which the concentrations of Zn, Pb, Cu, Ni and Cr in mg/kg were determined by multiplying the percentage content by this factor (formula 2). This allowed all data in Table 2 to be presented in mg/kg, ensuring the ac curacy of the assessment of the spatial variability of metals in different river sections.

Table 2. Concentration of heavy metals in bottom sediments of rivers in Transcarpathia, mg/kg

Point	Zn	Pb	Cu	Ni	Cr
Uzhhorod	15.3 ± 1.5	5.4 ± 0.5	5.9 ± 0.6	7.5 ± 0.8	11.4 ± 1.1
Pidpolozzia	1.4 ± 0.1	5.2 ± 0.5	4.3 ± 0.4	7.7 ± 0.8	10.4 ± 1.0
Kolchyno	26.1 ± 2.6	5.7 ± 0.6	6.9 ± 0.7	7.3 ± 0.7	13.0 ± 1.3
Dovhe	23.9 ± 2.4	6.2 ± 0.6	6.8 ± 0.7	6.9 ± 0.7	11.5 ± 1.1

Table 2. Continued

Point	Zn	Pb	Cu	Ni	Cr
Rakhiv	10.9 ± 1.1	4.4 ± 0.4	4.8 ± 0.5	7.2 ± 0.7	8.3 ± 0.8
Vylok	33.4 ± 3.3	6.4 ± 0.6	9.5 ± 1.0	8.2 ± 0.8	10.9 ± 1.1
Tiachiv	12.6 ± 1.3	–	3.9 ± 0.4	5.1 ± 0.5	6.3 ± 0.6
Chop	89.9 ± 9.0	8.9 ± 0.9	9.7 ± 1.0	8.3 ± 0.8	11.6 ± 1.2

Source: developed by the authors

In the work of S.A. Baliuk *et al*. (2023), the following limits are specified for the first suitability class: Zn ⩽ 100 mg/kg, Cu ⩽ 50 mg/kg, Pb ⩽ 50 mg/kg, Ni ⩽ 25 mg/kg, and Cr ⩽ 40 mg/kg. From Table 2, it is evident that the Zn value recorded in Chop (89.9 mg/kg) is close to the upper limit. This indicates the presence of a local anthropogenic impact, particularly from the significant transport infrastructure - border crossing points and railway lines. In Vylok and Kolchyno, the Zn value is three times lower than the limit, and in Pidpolozzia, it is significantly below even the natural background level. Similar spatial variations of zinc were observed by M. Sojka & J. Jaskuła (2022) in Polish rivers. Other locations show intermediate concentrations, which suggests a weak anthropogenic influence. Pb concentrations varied from 4.4 to 8.9 mg/kg. The maximum was recorded in Chop, where likely sources are road transport and domestic waste. In Kolchyno, Vylok, and Uzhhorod, concentrations are at a moderate level, indicating a combination of background concentrations and local anthropogenic impact. Rakhiv recorded the lowest concentration, while no Pb content was detected in Tiachiv. This confirms the results of V. Khomenchuk *et al*. (2022), where areas with a low population density and fewer sources of pollution had minimal Pb concentrations. Overall, all Pb values in the region do not exceed the aforementioned limits, though in combination with other metals, they could cause a synergistic toxic effect.

The maximum Cu values in Chop and Vylok are likely due to agricultural activity and natural processes. In Pidpolozzia and Rakhiv, concentrations are at a background level, while the lowest Cu concentration is in Tiachiv, which is characteristic of unpolluted zones and is related to the geochemical and landscape diversity of the river. These patterns are supported by the data from J. Muneer *et al*. (2022), who showed that the impact of anthropogenic sources on Cu accumulation is more noticeable in the lower reaches of rivers than in mountainous areas. Ni concentrations were in the range of 5.1-8.3 mg/kg, which is below the limit and likely also reflects the natural geochemical background, as noted in S.A. Baliuk *et al*. (2023). The lowest value was also in Tiachiv. The maximum Cr concentrations were observed in Kolchyno, linked to its geological origin (volcanic rocks at the foot of the Volcanic Ridge). Moderate levels were found in Dovhe, Chop, Uzhhorod, and Vylok, while the lowest were in Rakhiv and Tiachiv. Similar trends were described in the work of M. Sojka & J. Jaskuła (2022), where geological origin determined the baseline level of Cr in sediments.

The data obtained can be integrated into regional environmental monitoring and ecological management systems, as they allow for the creation of detailed maps of element accumulation across riverine ecosystems. This, in turn, enables the identification of areas with a potentially elevated anthropogenic impact and the assessment of the effectiveness of control measures. The data can also be used for the environmental certification of territories, including the delineation of specific areas with their natural background and potential ecological risks. The results of this screening study enable the identification of risk zones during emergencies (in case of accidental spills of toxic or radioactive elements into riverine ecosystems), which would increase the effectiveness of rapid response and, accordingly, reduce the negative impact on aquatic ecosystems and ensure public safety. The work of M. Hrechaniuk *et al*. (2023), which studied the activity of natural and technogenic radionuclides in the bottom sediments of Lake Bryt in the Chornobyl Exclusion Zone, is similar to the present study on Transcarpathian rivers. Like this study, the authors consider bottom sediments to be an indicator of the accumulation of natural (U-, Th-series, K-40) and technogenic (Cs-137) radionuclides and analyse the spatial variability of their distribution.

A common feature of both works is the use of γ-spectrometric analysis and a focus on the influence of geological and anthropogenic factors on the radioecological state of aquatic ecosystems.

It is important to note that bottom-dwelling organisms and ichthyofauna are particularly susceptible to the accumulation of radionuclides and heavy metals, as they use bottom sediments as a habitat or food source. A study by F. Jamil Emon *et al*. (2023) found that a high content of toxic elements in the lower reaches of rivers can lead to their bioaccumulation in fish tissues, which potentially reduces biodiversity and the stability of riverine ecosystems. Research by M. Shahjahan *et al*. (2022) shows that the accumulation of metals damages organs, alters respiratory and digestive functions, and affects the growth of living organisms. The results obtained in this study are important within the context of the "bottom sediments – ichthyofauna" system, as bottom sediments act as the primary depot for radionuclides and heavy metals, which fish can then accumulate in their tissues through food chains. Such patterns are confirmed by studies from B.M. Mitrović *et al*. (2025) and T. Brázová *et al*. (2025).

The data from this study have practical value for future monitoring: they allow for the determination of the bioaccumulation levels of heavy metals and radionuclides in ichthyofauna. The "bottom sediments – ichthyofauna" system can be used as an effective indicator of the ecological state of aquatic ecosystems. Thus, the study's results show that the content of radionuclides and heavy metals in the bottom sediments of Transcarpathian rivers has a clear spatial variability, which is due to a combination of natural and anthropogenic factors. In the lowland areas of the region with developed urbanisation, transport infrastructure, and agricultural activity, an increased accumulation of radionuclides and metals (especially Zn, Pb, Cu, and K-40) is observed. This is positively influenced by the high ability of fine-grained sediments and organic matter to sorb these elements. In mountainous areas with fast-flowing currents and a predominance of coarse-grained bottom sediments, the accumulation of radionuclides and metals is significantly lower. This is explained by the low adsorption capacity of the sediments and active hydrodynamic processes. Furthermore, the Th/U ratio indicates the mineralogical diversity of the deposits, while the specific activity of Cs-137 shows a minimal anthropogenic impact of technogenic origin. Overall, the results obtained make it possible to assess the nature of the spatial distribution of elements in bottom sediments, identify areas with a potentially high risk of metal and radionuclide accumulation, and can be integrated into a regional water body monitoring system. The data can also be used for the environmental certification of territories and for establishing risk zones in emergencies.

CONCLUSIONS

The conducted screening of the bottom sediments in Transcarpathian rivers indicates the presence of spatial variability in the content of natural (K-40, U- and Th-series) and technogenic (Cs-137) radionuclides, as well as heavy metals (Zn, Pb, Cu, Ni, Cr). This variability is caused by a combination of natural geochemical factors and local anthropogenic impacts. The total specific activity of the U- and Th-series is highest in low-lying urbanised areas (Uzhhorod, Vylok), while the maximum K-40 content is found in Chop, Kolchyno, and Pidpolozzia. This is linked to volcanogenic-sedimentary rocks, alluvial deposits, and the potential use of potassium-containing fertilisers. The Th/U ratio, within the range of 0.63-1, reflects the mineralogical heterogeneity of the bottom sediments and the geochemical differences between various river sections. Technogenic Cs-137 generally has low activity (2.9-7.0 Bq/kg), however, local increases were found in Dovhe and Kolchyno due to the accumulation capacity of fine-grained silt and organic matter.

Analysis of heavy metals shows elevated concentrations of Zn, Pb, and Cu in urbanised areas (Chop, Uzhhorod), which indicates local anthropogenic pollution from the presence of important transport infrastructure, such as border crossing points and railway lines. The lowest metal values were found in the mountainous part of the territory (Tiachiv, Rakhiv, Pidpolozzia). Overall, all heavy metal concentrations do not exceed the established environmental limits for bottom sediments, but local increases were recorded in the urbanised part of the region with transport infrastructure (in Chop). The results obtained provide an important basis for a further assessment of the bioaccumulation of pollutants by indigenous ichthyofauna, as well as for monitoring the state of the region's riverine ecosystems. Analysing concentrations in bottom sediments makes it possible to identify areas with an increased risk of accumulation, assess the impact on the biota, and create spatial distribution maps of elements to identify areas with increased anthropogenic pressure. The prospects for further research lie in assessing the bioaccumulation of radionuclides and heavy metals by local ichthyofauna and predicting the impact on the population structure of aquatic organisms. Additional studies could include long-term monitoring of changes in the geochemical state of bottom sediments, taking into account seasonal fluctuations in flow and element concentrations. This would allow for an assessment of the dynamics of element accumulation and migration depending on the season and for predicting the potential impact on riverine ecosystems.

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CONFLICT OF INTEREST

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Скринінг вмісту природних (^{238}U і ^{232}Th-рядів, ^{40}K) і техногенного (^{137}Cs) радіонуклідів, а також важких металів у донних відкладах річок Закарпаття

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Анотація. Донні відклади є важливим індикатором стану річок, оскільки здатні акумулювати природні та техногенні речовини, відображаючи фонові геохімічні особливості і антропогенне навантаження. Метою дослідження був аналіз вмісту природних і техногенного радіонуклідів та важких металів у річках Закарпаття для виявлення закономірностей їхнього розподілу та подальшої оцінки біоакумуляції у системі «донні відклади – іхтіофауна». Для досягнення мети було застосовано γ-спектрометричний аналіз на комплексі «ORTEC» та рентгенофлуорисцентне визначення металів за допомогою аналізатора «Elvax Pro». Зразки було відібрано у 2023-2024 рр. з восьми пунктів у межах річок Уж, Латориця, Боржава та Тиса. Результати показали просторову варіабельність, зумовлену поєднанням геологічних, морфологічних та антропогенних чинників. Сумарна активність природних радіонуклідів (U-і Th- рядів) виявлена в межах 340-534 Бк/кг, а максимальні значення були виявлені в межах пунктів Ужгород, Вилок, Чоп. Найвищу активність природного радіонукліду K-40 (522-533 Бк/кг) було зафіксовано в районах із присутністю калієвих мінералів та аграрним навантаженням – Підполоззя, Кольчино та Чоп. Cs-137 мав низьку активність (2,9-7,0 Бк/кг), з локальним підвищенням у дрібнозернистому намулі. Геохімічний індекс Th/U (0,63-1) показав мінералогічну різноманітність седиментів. Аналіз вмісту важких металів виявив просторові відмінності: концентрації Zn в межах 1,4-89,9 мг/кг, Pb - 4,4-8,9 мг/кг, Cu - 3,9-9,7 мг/кг, Ni - в межах 5,1-8,3 мг/кг, а Cr - від 6,3 до 13,0 мг/кг. Найвищі значення елементів виявлені в межах урбанізованих територій (Ужгород, Чоп), а найнижчі – у гірських районах із мінімальним антропогенним впливом. Концентрації важких металів не перевищували екологічні нормативи, проте локальні максимуми показали потенційне забруднення. Практичне значення цього дослідження полягає у використанні його результатів для екологічного моніторингу, прогнозування міграції елементів та оцінки їхньої біоакумуляції у водних трофічних ланцюгах

Ключові слова: геохімічний моніторинг; фонове радіаційне випромінювання; річкові седименти; токсичні елементи; річкові екосистеми