

# **RADIATION MAPPING OF THE BORZHAVA RIVER AREAS, TISZA BASIN: PECULIARITIES OF RADIONUCLIDE DISTRIBUTION AND ORGANISATIONAL AND MANAGERIAL SUPPORT OF MOUNTAINOUS TERRITORIES**

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The article presents the results of radioecological studies of the Borzhava River, which is an integral part of a comprehensive study of the Tisza River water systems and their impact on the hydrological balance of the region. To study the processes of migration, accumulation, and prediction of the behavior of gamma-active nuclides (natural  $^{40}\text{K}$ ,  $^{238}\text{U}$ , and  $^{232}\text{Th}$  series and man-made  $^{137}\text{Cs}$ ), the spatial and seasonal distribution of these nuclides in the river bottom sediments was mapped. Seasonal fluctuations in the concentration of  $^{137}\text{Cs}$ ,  $^{40}\text{K}$ ,  $^{238}\text{U}$ , and  $^{232}\text{Th}$  activity in spring, autumn, and summer were determined. A multivariate statistical analysis was carried out, establishing the degree of correlation between the sampling points regarding the content of gamma-active nuclides. The research and generalization of the regularities of distribution, migration, and accumulation of gamma-active nuclides can be used to develop regulatory and legal documentation.

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## **INTRODUCTION**

The study of the patterns of accumulation and translocation of gamma-active nuclides makes it possible to more effectively address the problematic consequences of environmental pollution, which has become especially relevant after the Chernobyl accident [1]. The problem of environmental contamination with gamma-active nuclides (GAN) is also exacerbated by the annual increase in the use of radioactive energy in various industries [2] and threats of aggressive countries, such as Russia, to use nuclear weapons. In addition, due to the occupation of certain territories of Ukraine by Russian troops, their actions, such as digging trenches where the radiation level was significant and raising radioactive dust with military equipment, caused severe problems in the field of radiation safety. In addition, given the natural and geological features of the territory of Ukraine, it is essential to note that in some areas, young sedimentary rocks also have increased radioactivity.

Radioecological monitoring is becoming a key tool in implementing radiation safety measures to restore environmental sustainability and ensure citizens' safety in such crisis situations. In this context, it is important to develop regulatory and legal documentation and draft regulations for the territory's environmental impact assessment and radiation mapping. The primary key is proper organizational and legal support by the relevant state institutions, focused on making flexible and prompt solutions.

Several modern studies are devoted to the problem of studying and assessing the content of radionuclides in soils, bottom sediments, air, and water bodies [3–11]. In this regard, the bottom sediments of water bodies deserve considerable attention, as they can accumulate pollutants (products of destruction of shores, soils, etc.).

Bottom sediments containing a significant amount of compounds, including HAPs, are formed in water bodies due to physical and chemical processes of coagulation and deposition of the dispersed phase of hardly soluble salts [12]. It is also important that the sediments of small rivers are relatively labile natural objects that well reflect the intensity and scale of anthropogenic environmental pollution.

Therefore, sediments' chemical and isotopic composition is an essential indicator of the ecological state of water systems and river basin areas, which is an integral part of assessing the environmental and geochemical state of the geological environment [12].

The mountain ranges of the Carpathians have a dominant function in shaping the air and water regimes of Transcarpathia and Eastern and Central Europe [12]. In addition, the Carpathians are the region where the largest river in Europe, the Tisza (the largest tributary of the Danube), originates. Radioecological surveys of the upper reaches of rivers are critical, as it is in the headwaters that trace elements and chemical composition are formed. The Borzhava is one of the largest tributaries of the Tisza River basin, which is why it deserves our attention, as it is strategically important for determining its impact on the ecological status of the Tisza and for developing effective water management strategies in this regional ecosystem. It is important to note here that small rivers can be good indicators of changes in the ecological state of the environment [13, 14], as they are very sensitive to anthropogenic pressures. Given that the Borzhava River flows near populated areas (given the large area and high levels of agricultural land contamination), it is essential to study the spatial and temporal trends in the distribution and accumulation of gamma-active nuclides in the bottom sediments of water bodies.

This paper presents the results of a radioecological study of spatial and temporal changes in radionuclide fluctuations carried out along the Borzhava River channel in the Tisza River basin. The regulations and procedures for establishing radiation indicators of the studied territories are considered: the scheme of sampling bottom sediments, features of low-background gamma spectrometric studies, and the possibility of using predictive models to develop radiation maps of HAP migration in the adjacent territories.

## 1. MATERIALS AND METHODS OF RESEARCH

The radioecological analysis of the Borzhava River bottom sediments is due to its high information content,

which allows for a better understanding of the dynamics of natural processes and will provide a scientific basis for the rational management of the region's natural resources.

The article presents the results of radiological analysis of the bottom sediments of the Borzhava River. The study was conducted in 2021–2022, including three seasons (spring, summer, autumn).

Sediment samples weighing 1500...2000 g were collected at fixed points (T1-T10) in 10 sites along the channel by hand from a depth of 0...15 cm using dredges (Fig. 1).

The coordinates of the sampling points (see Fig. 1) were determined using GPS navigation and recorded using signs installed on the shore.



*Fig. 1. Sampling points of the Borzhava River.*

- Notes: T1 – beginning of Borzhava river; T2 – beginning of Bereznyky village; T3 – Bereznyky - Keretski village; T4 – Keretski village – beginning of Kushnytsia village; T5 – Kushnytsia village – village Bronka; T6 – Bronka – Dovhe village; T7 – Dovhe – Pryborzhavske village; T8 – Lukovo village; T9 – Imstychovo - Bilky village; T10 – Bilky – Rakovets village*

The coordinates of the sampling points (see Fig. 1) were determined using GPS navigation and recorded using signs installed on the shore.

The meticulously chosen scheme of sampling of the Borzhava River (see Fig. 1) enables us to evaluate the processes of radionuclide migration along the riverbed and pinpoint the primary zones of isotope accumulation within it. This precision is crucial for modeling and forecasting the state of the study area and adjacent territories, lending our study high credibility.

The sample preparation was meticulously carried out in strict accordance with the standard method [15]. This adherence to rigorous scientific protocols ensures the equilibrium of radionuclides of the  $^{238}\text{U}$  and  $^{232}\text{Th}$  series, with the samples placed in sealed containers (plastic bags) for three weeks before measurement.

The determination of the specific activity of gamma-active nuclides ( $^{238}\text{U}$  ( $^{214}\text{Pb}$ ,  $^{214}\text{Bi}$ ,  $^{226}\text{Ra}$ ),  $^{232}\text{Th}$  ( $^{212}\text{Pb}$ ,  $^{212}\text{Bi}$ ,  $^{228}\text{Ac}$ ,  $^{208}\text{Tl}$ ),  $^{40}\text{K}$ ,  $^{137}\text{Cs}$ ) in the sediments was carried out using the state-of-the-art semiconductor  $\gamma$ -spectrometric complex “ORTEC” with a 150 cm<sup>3</sup> HPGe

detector. This advanced equipment allowed us to constantly monitor the drift of the spectrometric complex's energy scale, resolution, and registration efficiency using point standard gamma-active sources  $^{57}\text{Co}$  and  $^{60}\text{Co}$  [12], enhancing the precision and reliability of our measurements.

It's crucial to emphasize that our data holds only immediate practical value if it's meticulously structured and visually presented. This fact is where the role of professional tools for spatial, statistical, and other types of analysis comes into play. These tools are essential for integrating and performing operational analysis and synthesis of large data sets. In our case, we utilized the ArcGIS 10.2.1 computer program widely used by scientists globally to work with geodata and present it in a visual format. This process is instrumental in solving various scientific problems [16–20].

The ArcGIS package functions are accessed through a graphical interface, a set of tools that depends on the software module. The input data was loaded using two methods: exporting directly from a Microsoft Excel

document and entering data using the built-in ArcMap table editor with interactive placement of sampling points on the map.

## 2. RESEARCH RESULTS

Radioecological monitoring of the state of small rivers, in particular, bottom sediments, plays a critical role in the sustainable restoration, conservation, and sustainable development of ecosystems. These studies make it possible to identify not only sources of pollution but also help to take measures to eliminate them.

The paper presents the results of mapping the spatial and seasonal (spring, autumn 2021, and summer 2022)

distribution of natural gamma-active nuclides  $^{40}\text{K}$ , series of  $^{238}\text{U}$  and  $^{232}\text{Th}$ , and anthropogenic  $^{137}\text{Cs}$  in the bottom sediments of the Borzhava River (Fig. 2).

According to the data obtained (see Fig. 2), it was found that the main contribution to the specific activity of HAPs is made by  $^{40}\text{K}$  (depending on the clark number of the element). The content of the  $^{40}\text{K}$  isotope in the bottom sediments during the study period (2021–2022) is in the range of 363.8...561.8 Bq/kg. It is important to note that our results are close to the content of  $^{40}\text{K}$  in the Dnipro River sediments (30...520 Bq/kg) [21].

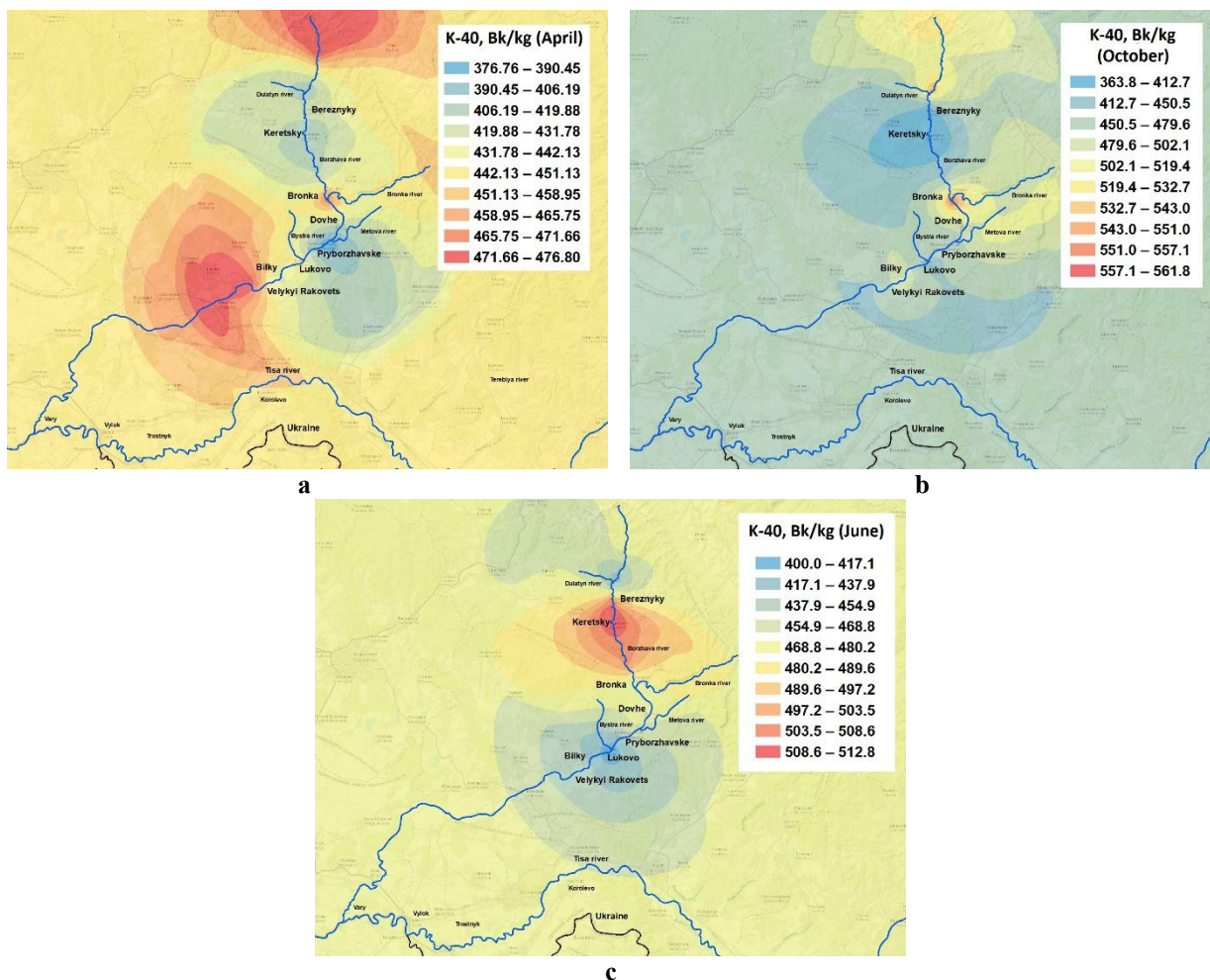


Fig. 2. Map of the distribution of specific activity of  $^{40}\text{K}$  in the Borzhava River basin by the state of their bottom sediments: a – April 2021; b – October 2021; c – June 2022

The comparison of Fig. 2,a-c shows that the values of the average content of the  $^{40}\text{K}$  isotope within one season are close at most points. At the same time, there are significant differences between the maximum and minimum recorded values, especially for the autumn period (minimum value – 364 Bq/kg, maximum value – 562 Bq/kg). However, it can be noted here that the zone of accumulation of natural  $^{40}\text{K}$  increases in area and becomes more pronounced during the transition from autumn to summer (due to an increase in precipitation and increased river flow in autumn, which washes out bottom sediments, and the opposite picture in summer, which contributes to a greater degree of siltation and

accumulation of radionuclides), which also allows predicting the future state of this territory.

For the spring period, an increase in the content of  $^{40}\text{K}$  in the bottom sediments of the Borzhava River in the upper part and downstream was determined, which obviously depends on geomorphological conditions, surface runoff, and the amount of potassium fertilizers applied to the soil [22] (with a decrease in the sampling point, the influence of human factors, such as agronomic planting of crops, increases).

The distribution of the specific activity of anthropogenic  $^{137}\text{Cs}$  for the period of spring-autumn 2021, and summer 2022 is shown in Fig. 3.

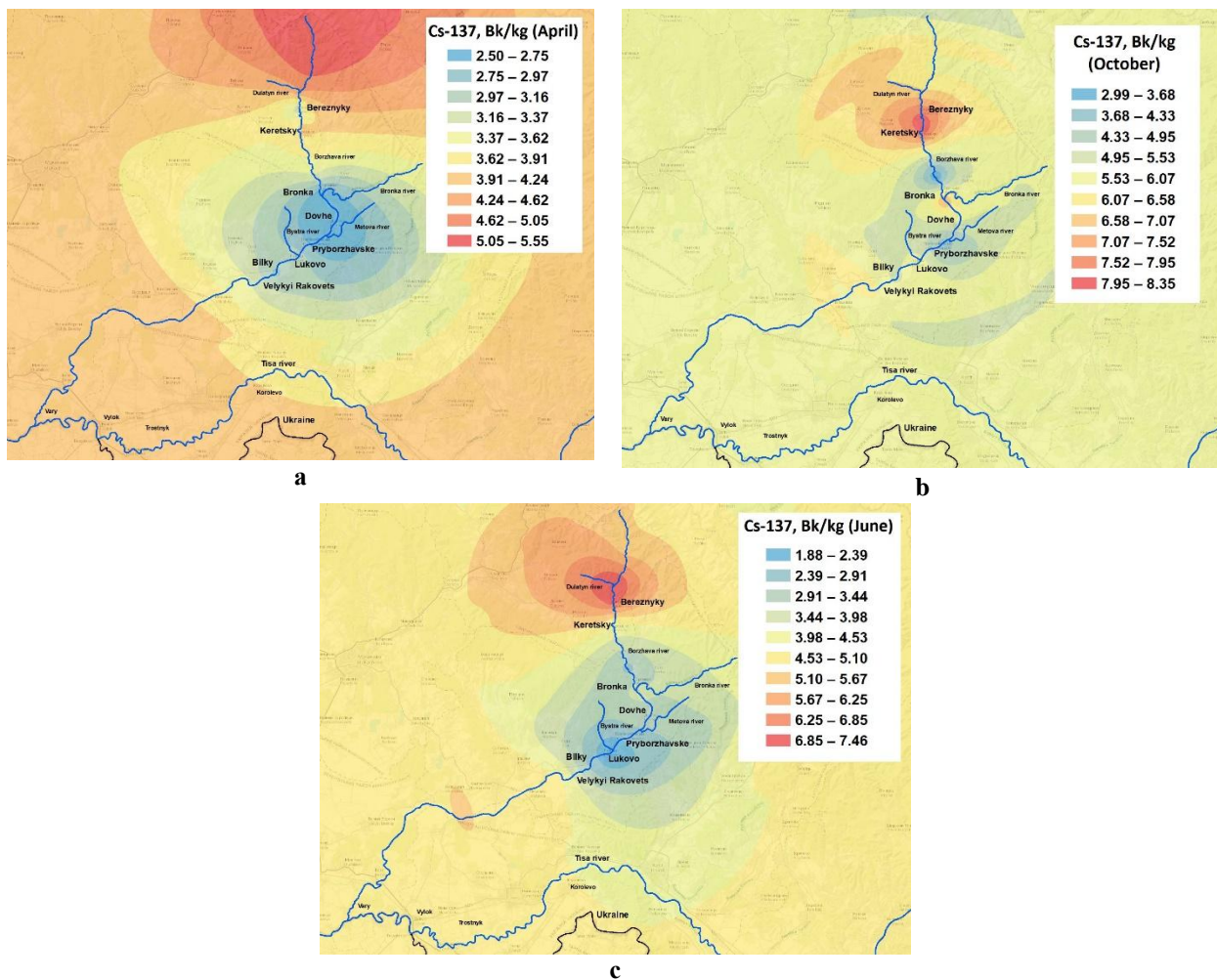


Fig. 3. Map of distribution of specific activity  $^{137}\text{Cs}$  in the Borzhava River basin by the state of their bottom sediments: a – April 2021; b – October 2021; c – June 2022

It was found that the content of  $^{137}\text{Cs}$  in sediments during the study ranged from 1.88 to 8.35 Bq/kg. The obtained data on the distribution of  $^{137}\text{Cs}$  content in the sediments of the Borzhava River are consistent with the results for sediments of small rivers of Transcarpathia, where the concentration of this radionuclide varies from 1.5 to 7 Bq/kg [23]. Similar (about 2.1-8.9) are the data on the distribution of  $^{137}\text{Cs}$  in the sediments of the Tisza River (the largest tributary of the Danube River) for the Transcarpathia region [18, 24], which indicates a low concentration of  $^{137}\text{Cs}$  in the study area.

Analysing the data of Fig. 3,a-c regarding the temporal distribution of  $^{137}\text{Cs}$ , it is possible to distinguish the zone of accumulation of  $^{137}\text{Cs}$  and the zone of reduced content.

The data from Fig. 3 reveals a significant pattern—the zone of accumulation of anthropogenic isotopes in the Borzhava River migrates downstream during the shift from spring to summer. This observation holds the potential for predicting the future displacement of such zones, a crucial factor in managing the hydro system.

It is important to note that in autumn (see Fig. 3), the concentration of radioactive cesium in the bottom sediments of the Borzhava River (as shown in the legend) slightly increases compared to spring and summer (maximum values: spring – 5.55 Bq/kg,

autumn – 8.35 Bq/kg, summer – 7.46 Bq/kg), but the accumulation area  $^{137}\text{Cs}$  for this season is the least pronounced. This is due to the fact that in autumn, the strength and duration of winds and precipitation increase, and the hydrodynamic activity of the water mass increases accordingly. The summer period is relatively low-water and the areas of radioactive contamination of bottom sediments with  $^{137}\text{Cs}$  were stable (natural gradual increase of the silt layer), which leads (see Fig. 3,c) to an increase in the area of localisation of this radionuclide. Obviously, the expansion of the accumulation zone of radioactive cesium also indicates a low activity of self-purification processes.

As demonstrated in this study, identifying accumulation zones in the bottom sediments of small rivers plays a pivotal role in practically implementing a system of rational use and adequate management of the hydro system. This application of our research findings underscores its relevance and importance.

It is known that decay products make the main contribution to terrestrial radioactivity in the natural uranium and thorium series. The concentration of the total specific activity (excluding  $^{40}\text{K}$ )  $^{232}\text{Th}$ ,  $^{238}\text{U}$  (Fig. 4) in the studied samples of the Borzhava River is shown in Fig. 4,a-c.

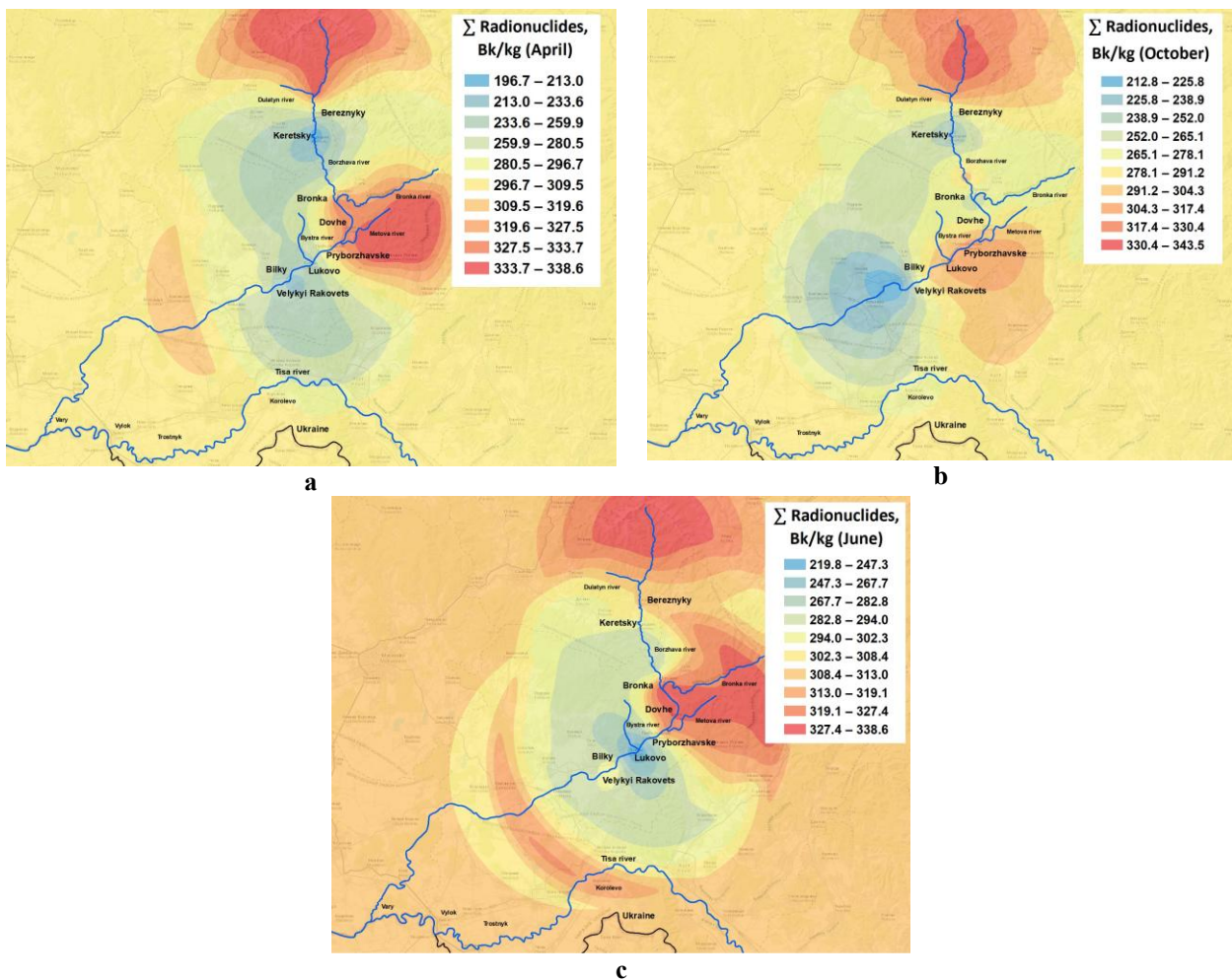


Fig. 4. Map of the distribution of the total specific activity of natural GANs (excluding  $^{40}\text{K}$ ) in the Borzhava River basin by the state of their bottom sediments: a – April 2021; b – October 2021; c – June 2022

The analysis of Fig. 4,a-c reveals two distinct accumulation zones and areas with reduced content of natural HAPs in the series  $^{232}\text{Th}$  and  $^{238}\text{U}$  for all seasons. This finding is significant as it provides a comprehensive understanding of the distribution of natural HAPs in the Borzhava River throughout the year. The migration of the HAN accumulation zone downstream from spring (see Fig. 4,a) to autumn (see Fig. 4,b) is a noteworthy observation, potentially influenced by the river's geomorphological features and the leaching of bottom sediments by rainwater.

Comparing the data of Fig. 4,b,c, it can be seen that the accumulation zone (lower reaches of the Borzhava River) becomes more pronounced during the transition from autumn to summer periods and there is a gradual increase in the total specific activity of HAN in the bottom sediments of this zone, which is obviously due to a decrease in precipitation and greater siltation (and therefore an increase in the total content of these radionuclides in the bottom sediments).

It is important to note that our mapping results can be used both to assess the prediction of the dynamics of the process of HAB migration in environmental objects (to assess the state of the environment and its impact on the river and the local population, to track changes in the riverbed, to identify new river areas) and to carry

out certification of the studied and adjacent territories. GIS in environmental monitoring is an effective tool in the decision-making support system for developing ecological safety measures in the context of military impact.

Systematizing our radioecological experiment data was a rigorous process requiring advanced mathematical statistics methods. The results of our multidimensional statistical processing of the content of the studied isotopes, based on the results of seasonal sampling of the Borzhava River bottom sediments, are presented in Fig. 5. The distance between the clusters in the figure reflects the level of affinity of the sampling points by the content of HAN, providing a clear visual representation of our findings.

Our research revealed an interesting pattern in the correlation between the sampling points and the content of HANs in sediments. The best correlation was observed for the spring-summer period (2021–2022), indicating a more stable equilibrium of HANs during this time. However, this correlation was not observed for the autumn period, suggesting a disturbance in the equilibrium of HANs in autumn, possibly due to water leaching, mechanical movement, or chemical reactions. This finding underscores the importance of considering seasonal variations in radioecological studies.

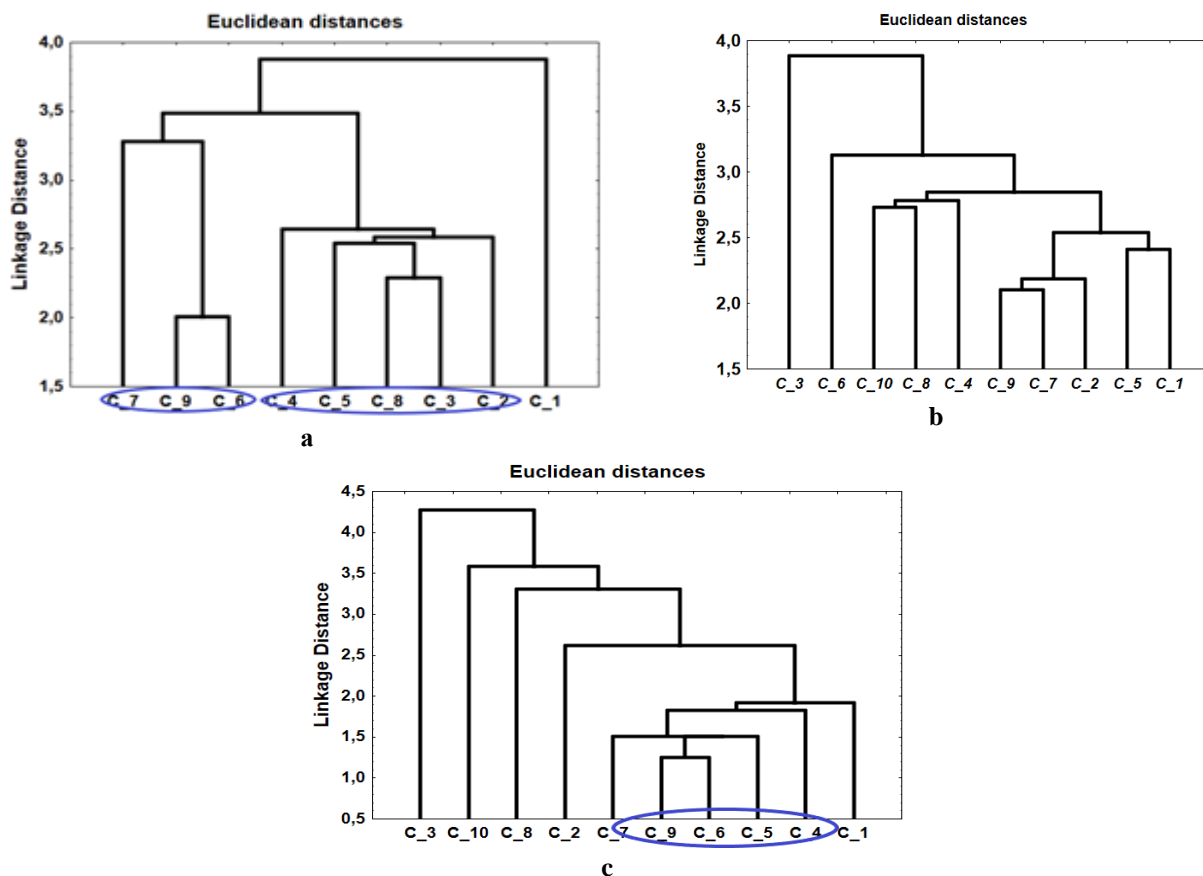


Fig. 5. Results of seasonal correlation: a – April 2021; b – October 2021; c – June 2022 between sampling points along the Borzhava riverbed

Conducting radioecological studies is an urgent task, especially nowadays, when the level of anthropogenic impact (military actions) on the environment is increasing daily. The results of the studies of the distribution, migration, and accumulation of HAPs in Borzhava River sediments will be used to develop regulatory documents, in particular, draft regulations for environmental impact assessment and audit, certification, and mapping in the evaluation of the state of water resources in the Tisza River basin, which will allow modelling the processes of HAP migration in different landscape areas and predicting the future state of facilities in large adjacent mountainous regions.

## CONCLUSIONS

Based on the results of the study, the spatial and seasonal patterns of distribution of gamma-active nuclides of natural and anthropogenic origin in the bottom sediments of the Borzhava River (Tisza River basin) were mapped and established. The relative constancy of natural and artificial radionuclides' activities for most sites within one season is shown, which indicates the absence of powerful sources of their intake.

It was found that the main contribution to the natural activity is made by  $^{40}\text{K}$  (363.8...561.8 Bq/kg). Comparing the seasonality of distribution, it can be more pronounced for spring and summer seasons compared to autumn, which is due to a number of factors (climatic factors, in particular, temperature

regime of the territory, duration of summer and winter seasons, type and intensity of precipitation).

The concentration of the total specific activity (excluding  $^{40}\text{K}$ ) of  $^{232}\text{Th}$ ,  $^{238}\text{U}$  shows two distinguished zones of HAN accumulation (the highest values) and zones of reduced content for all studied periods. Generally, the pattern typical for the distribution of  $^{40}\text{K}$  is observed – the accumulation zone of  $^{232}\text{Th}$ ,  $^{238}\text{U}$  in spring and summer increases in area and becomes more pronounced compared to autumn.

The distribution of radiocaesium (of exogenous origin) in the bottom sediments of the Borzhava River varies from 1.88 to 8.35 Bq/kg, which indicates a low concentration of  $^{137}\text{Cs}$  in the studied region.

Mapping the migration and accumulation of radionuclides in sediments shows the importance of using various tools and programs to monitor environmental pollution in conflicts and crises (military operations).

Although the situation in the study areas is currently within the environmental optima, it should be remembered that military operations have a powerful impact on the environment and can make adjustments. Given this, low-background gamma spectrometric surveys are important because they allow for analysing of the level of radiation contamination in various ecosystems, determining the extent of contamination, and helping to develop protection strategies and effectively manage radiation risks in military conflicts.

The results provide important information about the distribution of gamma-active nuclides in the Borzhava

River. These data may play a vital role in the development of regulatory documentation, emphasizing the importance of this research for the eco-security of mountain areas and the future planning of legal documentation.

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**РАДІАЦІЙНЕ КАРТУВАННЯ БАСЕЙНУ р. ТИСА (р. БОРЖАВА):  
ОСОБЛИВОСТІ ПОШИРЕННЯ РАДІОНУКЛІДІВ  
ТА ОРГАНІЗАЦІЙНО-УПРАВЛІНСЬКИЙ СУПРОВІД ГІРСЬКИХ ТЕРИТОРІЙ**

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Представлено результати радіоекологічних досліджень р. Боржава, яка є невід'ємною частиною комплексного вивчення водних систем р. Тиса, та їх вплив на гідрологічний баланс регіону. З метою дослідження процесів міграції, акумуляції та прогнозування поведінки гамма-активних нуклідів (природних  $^{40}\text{K}$ , рядів  $^{238}\text{U}$  і  $^{232}\text{Th}$  та техногенного  $^{137}\text{Cs}$ ) проведено картування просторового та сезонного їх розподілу у донних відкладах річки. Встановлено сезонні коливання концентрації активності  $^{137}\text{Cs}$ ,  $^{40}\text{K}$ ,  $^{238}\text{U}$ ,  $^{232}\text{Th}$  у весняний, осінній і літній періоди. Проведено багатовимірний статистичний аналіз, який дозволив встановити ступінь кореляції між точками відбору за вмістом гамма-активних нуклідів. Проведені дослідження і узагальнення закономірностей розподілу, міграції та акумуляції гамма-активних нуклідів можна використовувати при розробці нормативно-правової документації та організаційно-управлінського супроводу екобезпеки гірських територій.