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Original Research

Activity Concentration of Natural Radionuclides in Surface Waters and Bottom Sediments Near Uranium Mining Sites and Environmental Impacts

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ABSTRACT

This research provides a radioecological assessment of surface waters and bottom sediments in the vicinity of conserved and reclaimed uranium mining sites in Northern Kazakhstan. Activities of natural radionuclides were determined, and distribution coefficients, radiological hazard indices, committed effective dose, and ecological contamination indices were calculated to evaluate radionuclide mobility and associated environmental risks. Gross alpha activity increases downstream along the Kutunguz River, while uranium isotope activities exceed background levels by 8–10-fold, indicating ongoing radionuclide migration from the conserved Shantobe uranium deposit. In contrast, the Balkhashin quarry, a closed hydrological system, demonstrates substantial accumulation of ^{228}Ra attributable to limited water exchange. Distribution coefficient analysis indicates high uranium mobility in flowing river systems and enhanced retention in closed water bodies. Although most radiological hazard indices remain within internationally accepted limits, localized radiological risk is observed in the quarry area. The committed effective dose from drinking water at the background site exceeds the WHO screening level but remains below the ICRP recommended limit. The obtained results indicate differences in the behavior of radionuclides in flowing and closed hydrological systems, as well as the persistent impact of conserved uranium mining facilities on aquatic ecosystems.

INTRODUCTION

Natural radionuclides occur ubiquitously in the environment at variable concentrations and, under typical conditions, do not pose significant risks to human health. Radionuclides detected in rocks, soils, waters, and the atmosphere primarily originate from the natural decay series of ^{238}U, ^{232}Th, and ^{40}K. However, their concentrations may increase as a consequence of mining activities or natural disturbances (Wu et al.2014). Mineral extraction, including open-pit mining and ore processing, generates substantial volumes of waste materials, and mine drainage waters are frequently discharged into surface water bodies. Accordingly, quantifying radionuclide concentrations, interactions, and mobility in environmental media represents a critical prerequisite for assessing radiation exposure and protecting public health.

Numerous studies have evaluated the environmental impacts of radionuclides worldwide (Kamunda et al. 2016; Galhardi et al.2017; Idrisheva et al.2025; Raji et al.2021). These investigations consistently demonstrate that uranium mining and related extractive activities elevate concentrations of uranium and its decay products in natural waters, and that adverse ecological effects may persist long after mining operations have ceased.

The Republic of Kazakhstan is characterized by a complex radioecological setting. Approximately 13% of its territory (about 350,000 km^2) is classified as radiation-affected, with more than one million residents living within these zones. Previous studies conducted in Kazakhstan (Saifulina et al.2023; Brzhanov et al.2020; Bersimbaev et al.2015; Zhumadilov et al.2025) have reported increased disease prevalence among populations residing near uranium mining sites, continued impacts of mine waste dumps on surface waters, and persistent environmental anomalies in affected regions.

Despite a significant number of researches devoted to the radioecological assessment of uranium mining territories, a comparative analysis of sites with different types of post-operational conditions (reclaimed and conserved facilities) within a single hydrological system remains limited.

The present research deals with carrying out a comparative analysis of the distribution of natural radionuclides in surface water systems differing in hydrological conditions (flowing and closed water bodies) and in the type of post-operational condition of uranium facilities. Particular attention is paid to identifying factors potentially influencing the migration of radionuclides and their redistribution among components of the aquatic environment.

For the quantitative characterization of radionuclide behavior, the distribution coefficient (Kd) is used, which is considered as an indicator of their mobility and their capacity for accumulation in bottom sediments. At the same time, Kd values are interpreted within the framework of comparative analysis and taking into account the limitations of available data, without constructing a deterministic model of the separation of influencing factors.

The scientific novelty of the work lies in the comparative assessment of the distribution of natural radionuclides in surface waters and bottom sediments in the vicinity of reclaimed and conserved uranium facilities within a single hydrological system, taking into account hydrological conditions. The obtained results are considered as a preliminary quantitative-descriptive assessment, given the limited sample size and the one-time seasonal nature of observations.

The objective of the present research is to determine the levels of radiological and ecological risk based on the measured activities of natural radionuclides in surface waters and bottom sediments in uranium mining areas of Northern Kazakhstan, as well as to conduct a comparative analysis of their distribution with consideration of hydrological conditions and characteristics of water exchange.

Field researches were conducted in 2025 in Northern Kazakhstan (Akmola Region, Sandyktau District) at sites associated with reclaimed and conserved uranium mines. Sampling was carried out during a single season (summer), since surface water bodies in the research area typically dry up in autumn, freeze in winter, and experience significant hydrological disturbances due to precipitation and runoff in spring.

2. MATERIALS AND METHODS

2.1.Description of the research area

The study area is situated within the Northern Kazakhstan uranium province, in the Sandyktau District of Akmola Region, administratively subordinate to the city of Stepnogorsk. The uranium deposits are located approximately 420 km from Astana, 170 km from Kokshetau, and about 450 km northwest of Stepnogorsk. The settlement of Shantobe, adjacent to the industrial mining site, lies 4 km to the east, while the village of Novokronshtadt is located 2 km to the west.

The Balkashin uranium mine was reclaimed in 2007 within the framework of the state program “Conservation of Uranium Mines and Reclamation of Territories after Deposit Development” (Government of the Republic of Kazakhstan, 2001). The territory of the mine consists of a waste dump and a quarry. During reclamation, works were carried out to restore the soil cover and to create a so-called reclamation layer providing favorable conditions for vegetation growth; the quarry bottom was flooded with water.

The Shantobe mine was conserved in 2014. It includes a group of deposits of different sizes (Vostok, Zvezdnoye). Ore extraction was carried out by underground mining methods; the mine area contains heap leaching sites, waste rock dumps, and several evaporation ponds. The main technology for uranium extraction at the deposits was heap sulfuric acid leaching.

The region is characterized by a sharply continental climate, with cold, snowy winters and hot, dry summers. The mean annual air temperature is +1.8 °C; average temperatures reach −16.8 °C in January and +20.4 °C in July. The mean annual wind speed is 5.3 m/s, and the average annual precipitation is 326 mm.

The principal surface water bodies in the study area are the Kishi-Kutunguz and Kutunguz rivers, which traverse former uranium mining territories. The investigation also included the Balkhashin quarry reservoir, located within the reclaimed Balkhashin uranium mine, and Lake Zhaksy-Zhalgyztau, situated at a considerable distance from direct anthropogenic influence. Lake Zhaksy-Zhalgyztau, approximately 16 km from the mining sites, was selected as a local background (reference) site. Within the framework of this research, the site of Lake Zhaksy-Zhalgyztau is considered as a conditionally background object (local background) used for comparative analysis within the research area. It should be noted, however, that independent historical or reference geochemical data were not employed due to their absence, which limits the possibility of rigorous verification of background values. In this regard, the obtained results should be interpreted as relative estimates allowing the identification of deviations in radionuclide distribution among the researched aquatic systems. Sampling locations were determined based on hydrogeological conditions, topography, and zones subject to anthropogenic impact (Fig. 1).

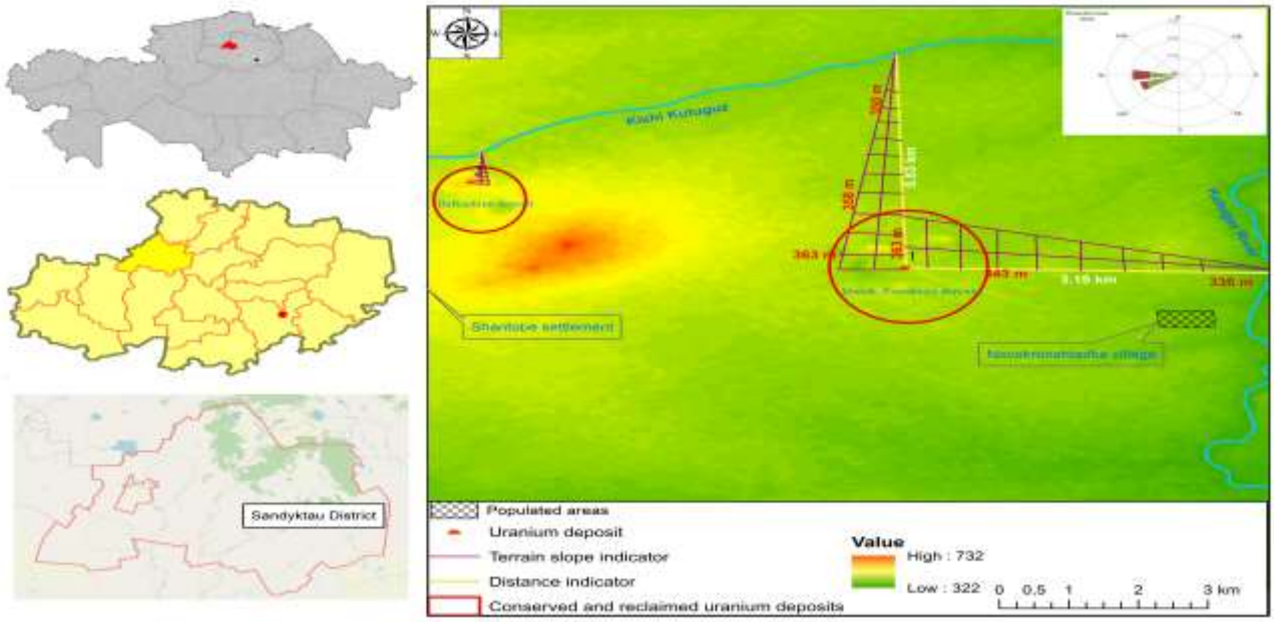

Fig.1: Location map of surface water bodies within the Balkhashin mining complex.
1 – Shantobe (Vostok, Zvezdnoe) decommissioned mine
2 – Balkhashin rehabilitated mine

2.2.Fieldwork

Radiological monitoring of water bodies represents one of the most methodologically demanding areas of environmental assessment due to the low activity concentrations of radionuclides and the need for strict sampling and analytical control. The initial stage of the present investigation included determination of gross alpha and gross beta activity in collected water samples (Dyussembayeva et al.2025).

Sampling was conducted in June 2025 during the summer hydrological period. Surface water samples were collected in accordance with the requirements of ST RK 1545-2006 (ST RK 1545-2006.2006), while bottom sediment sampling followed GOST 17.1.5.01-80 (GOST 17.1.5.01-80.1980). Bottom sediments were obtained from a depth of 5–10 cm using a Van Veen grab sampler, with individual sample masses ranging between 500 and 1000 g.

All collected materials were placed in airtight polyethylene containers and transported to the laboratory for subsequent analysis. Prior to water sampling, collection bottles were rinsed three times with the sampled water to minimize potential contamination. Sediment samples were stored in 1 kg polyethylene bags, whereas water samples were collected in 5000 mL sampling bottles. Immediately after collection, all samples were delivered to the laboratory. Owing to the considerable transport distance, water samples were preserved by acidification with nitric acid (HNO_3) to achieve $pH < 1$, using 100 mL of concentrated HNO_3 per 5 L of water.

In total, 10 samples were collected within the study area, comprising 5 surface water samples and 5 bottom sediment samples (Fig.2).

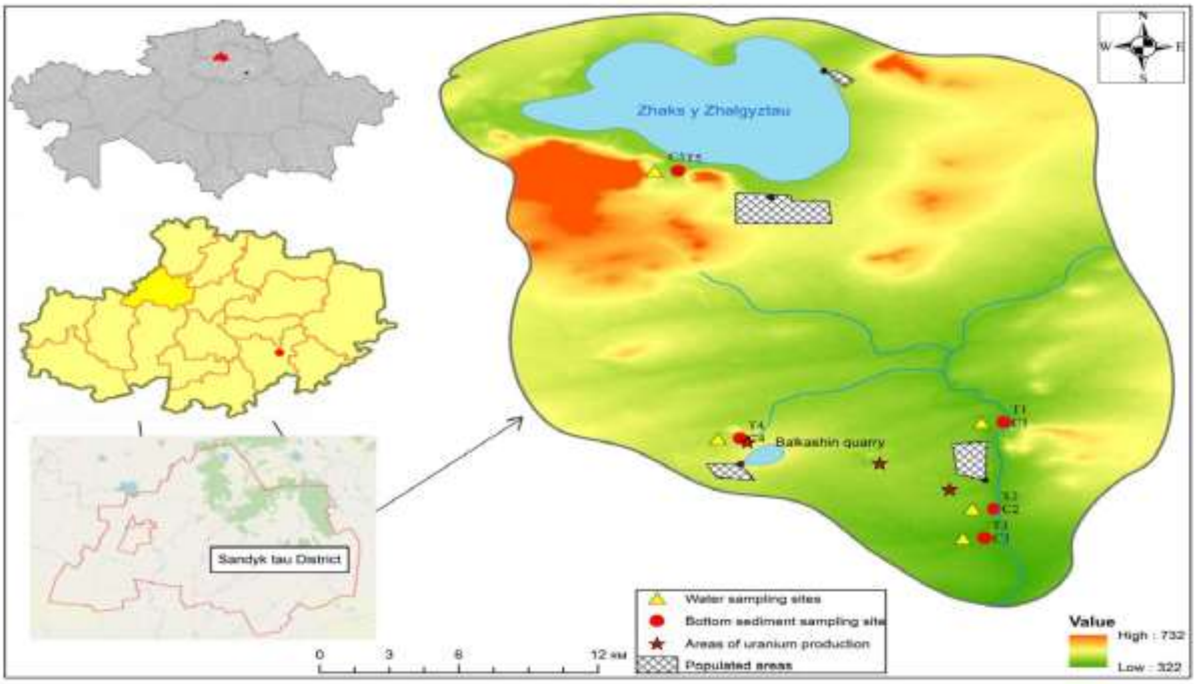

Fig.2: Distribution of sampling points in the study area. T – bottom sediment samples, C – water samples

2.3. Laboratory Analysis

Prior to analysis, samples underwent standardized laboratory preparation. Organic debris, roots, vegetation, and coarse mineral fragments were removed. Sediment samples were initially air-dried and subsequently oven-dried at 110 °C for 24 hours until constant weight was achieved. The activities of ^{226}Ra, ^{232}Th, and ^{40}K in bottom sediments were determined using an Atomtech MKS-AT1315 beta–gamma spectrometer (Minsk, Belarus). The permissible relative measurement uncertainty was ±15%. Gamma-emitting radionuclide spectra were processed using a multichannel analyzer (MCA) and PCA software.

Activities of ^{234}U and ^{238}U in sediment samples were measured using an MKS-01A “Multirad” instrument manufactured by Amplitude JSC (Zelenograd, Russia). Gamma spectrum analysis was performed using the “Progress” software package (Amplitude JSC, Zelenograd, Russia). The uncertainty associated with specific activity determination was approximately ±20–30% of the measured values.

In water samples, gross alpha and gross beta activity, as well as volumetric activities of ^{226}Ra, ^{228}Ra, ^{210}Po, and ^{210}Pb, were determined using a UMF-2000 alpha–beta radiometer in combination with radiochemical separation techniques.

Prior to measurement, water samples were subjected to preliminary concentration and radiochemical treatment, including co-precipitation and selective separation of target radionuclides. Control of chemical yield was carried out using tracers; the recovery efficiency ranged from 70% to 90%, and the obtained results were corrected with consideration of the yield.

The limits of detection (LOD), calculated based on counting statistics and background measurements, were on the order of 0.01–0.05 Bq/L for alpha-emitting radionuclides and 0.02–0.1 Bq/L for beta-emitting radionuclides. Quality assurance and quality control (QA/QC) included the analysis of blank samples, replicate measurements, and standard reference materials. The discrepancy between replicate measurements did not exceed 10–15%, and the contribution of blanks was below the detection limit or did not exceed 5% of the measured values.

Analytical uncertainty was evaluated taking into account both instrumental measurement errors and uncertainties associated with radiochemical procedures, including correction for chemical yield.

The calculated radiological and geochemical indices (Ra_eq, AEDE, K_d, CF, etc.) in the present research were determined based on the mean values of measured activities without explicit propagation of analytical uncertainties. Therefore, the obtained values should be regarded as estimated quantities, primarily suitable for comparative analysis.

In interpreting the results, it was taken into account that these uncertainties may affect the absolute values of the indices; however, they do not significantly influence the identified relative differences between the sites or the general patterns of radionuclide distribution.

Confidence intervals and sensitivity analysis were not performed in this research due to the limited sample size and the one-time nature of observations. The application of uncertainty propagation methods and statistical analysis is considered advisable in future work to improve the accuracy of quantitative assessment of radiological parameters.

Radiochemical and radiometric analyses were conducted at the accredited testing laboratory of the Institute of Radiobiology and Radiation Protection, Astana Medical University. The laboratory holds Accreditation Certificate No. KZ.T.01.1431 (20 August 2024) and operates in accordance with ISO/IEC 17025:2009 standards of the Republic of Kazakhstan, issued by the International Organization for Standardization (International Organization for Standardization.2019).

Statistical analyses were performed using Microsoft Excel and Statistica 6.0 software in accordance with standard statistical methodologies.

2.4.Distribution coefficient of radionuclides in sediments and water

The distribution of radionuclides in sediments and water was calculated using the following equation (1).

$$Kd\ (l/kg) = Asediment\ (Bq/kg)/Awater\ (Bq/L) \qquad (1)$$

Kd (l/kg): distribution coefficient, (l/kg)
Asediment (Bq/kg): is the concentration in sediments, Bq/kg
Awater (Bq/L): is the concentration in water, Bq/L.

2.5. Radiological hazard assessment

Radiological hazard to the local population associated with radionuclides in bottom sediments was evaluated using established international indices. These included radium equivalent activity (Ra_eq), absorbed dose rate (ADR), annual effective dose equivalent (AEDE), and the internal (H_in) and external (H_ex) hazard indices. In addition, the committed effective dose (CED) resulting from radionuclide ingestion through surface water consumption was calculated.

Dose calculations were based on an assumed water consumption rate of 2 L per day (730 L per year) and dose coefficients recommended by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR.2000) and the World Health Organization (World Health Organization.2004). Radionuclide intake via drinking water was assessed exclusively for sampling point 5 (Lake Zhaksy-Zhalgyztau), which serves as a drinking water source for residents of Shantobe and Novokronshtadt. For the remaining sites (sampling points 1–3: the Kutunguz River and the Balkhashin quarry technological reservoir), radiological and ecological hazard assessments were based on radionuclide activities measured in bottom sediments.

2.5.1. Radium equivalent (Ra_eq)

Radiation exposure was expressed in terms of radium equivalent activity (Ra_eq), calculated using Equation (2). The recommended upper limit for Ra_eq is 370 Bq/kg, corresponding to an effective gamma dose of approximately 1.5 mGy/year (Beretka and Mathew, 1985).

$$Ra\_eq = A\ Ra + (1{,}43 \times A\ Th)) + (0{,}077 \times A\ K\ ) \quad (2)$$

A Ra, A Th, A K: are the concentrations of the corresponding radionuclides (Bq/kg).

2.5.2. Absorbed dose rate (ADR)

The absorbed dose rate at 1 m above ground level was calculated assuming uniform radionuclide distribution in sediments, according to Equation (3). The safety limit recommended by the International Commission on Radiological Protection (ICRP.1990) is 1000 nGy/h, while UNSCEAR (UNSCEAR.2000) recommends a reference level of 1500 nGy/h.

$$ADR=0.462ARa+0.604ATh+0.0417AK \quad (3)$$

A: is the concentration of the corresponding radionuclide in Bq/kg.

2.5.3.Annual effective dose equivalent (AEDE)

The effective dose of ionizing radiation received by an individual as a result of external gamma radiation emitted from soil or bottom sediments over the course of a year. The annual effective dose equivalent (AEDE) represents the effective dose received by an individual due to external gamma radiation from sediments over one year. AEDE was calculated using Equation (4). The recommended annual dose limit for the public from artificial sources of ionizing radiation is 1 mSv (Akuo Ko et al.2025).

$$AEDE=D\times CF\times OF\times T\times 10^{-6} \quad (4)$$

D: is the absorbed gamma dose rate

T: is the annual exposure time (8760 h);

CF**:** is the conversion coefficient from air kerma to effective dose (0.7 $Sv\cdot Gy^{-1}$);

OF: is the outdoor occupancy factor (0.2);

10^{-6}: is used to convert nGy to mGy so that the final result is expressed in $mSv\cdot year^{-1}$.

2.5.4. Internal and External Hazard Indices

To ensure radiological safety, the internal (H_in) and external (H_ex) hazard indices must be less than unity, indicating an acceptable level of radiation risk. Natural radionuclides present in soils and bottom sediments contribute to external gamma radiation exposure of the population. A value of 1 corresponds to the maximum permissible radium equivalent activity (370 Bq/kg), which is associated with an effective annual dose of 1 mSv, as recommended by the International Commission on Radiological Protection (ICRP.1990).

Both indices were calculated using Equations (5) and (6), taking into account radium and uranium isotopes (^{226}Ra, ^{234}U, and ^{238}U):

$$Hin = (ARa/185) + (ATh/259) + (AK/4810) \quad (5)$$

$$Hex = (ARa/370) + (ATh/259) + (AK/4810) \quad (6)$$

A: represents the activity concentration (Bq/kg) of the corresponding radionuclide.

2.5.5. Committed Effective Dose (CED)

The committed effective dose (CED) was calculated to evaluate radiological risk associated with long-term ingestion of radionuclides through drinking water consumption. The calculation was performed exclusively for sampling point 5 (Lake Zhaksy–Zhangyztau), as this water body serves as a drinking water source for residents of the Shantobe and Novokronshtadt settlements.

The committed effective dose (CED) was calculated to evaluate radiological risk associated with long-term ingestion of radionuclides through drinking water consumption using the following equation (7). The calculation was performed exclusively for sampling point 5 (Lake Zhaksy–Zhalgyztau), as this water body serves as a drinking water source for residents of the Shantobe and Novokronshtadt settlements.

$$CED=C_i\times V\times DCF_i \qquad (7)$$

C_i: is the activity concentration of the radionuclide (Bq/L)
V: is the annual water consumption (730 L/year)
DCF_i: is the dose conversion factor (Sv/Bq)

2.6. Ecological Contamination Indices

2.6.1. Contamination Factor (CF)

The Contamination Factor (CF) is widely applied in environmental geochemistry to assess the degree of contamination of soils and bottom sediments by chemical elements (Håkanson.1980) and is calculated using the following Equation (8). Although originally developed for heavy metals, its applicability to radionuclide contamination has been demonstrated in recent researches (Bessa et al.2025; Severinenko et al.2023).

$$CF_i = C_i / C_i\text{,background} \qquad (8)$$

CF_i: is the contamination factor of a radionuclide
C_i: is the measured activity of the radionuclide in bottom sediments at the sampling site (Bq/kg)
$C_i$background: is the background activity of the same radionuclide determined for the reference (background) water body (Bq/kg).

The contamination levels are classified as follows:CF < 1 - low or no contamination;1 ≤ CF < 3 - moderate contamination;3 ≤ CF < 6 - considerable contamination;CF ≥ 6 - high contamination.

2.6.2. Pollution Load Index (PLI)

The Pollution Load Index (PLI) provides an integrated assessment of overall environmental contamination and was calculated using Equation (9):

$$PLI=(CF1\times CF2\times\ldots\times CFn)1/n \qquad (9)$$

PLI: is the pollution load index
CF_1–CF_n: are the contamination factors of individual radionuclides
n: is the number of radionuclides included in the calculation in the present study, namely ^{226}Ra, ^{232}Th, and ^{40}K.

2.6.3. Enrichment Factor (EF)

The Enrichment Factor (EF) was calculated using Equation (10) to evaluate the degree of anthropogenic influence on radionuclide concentrations in bottom sediments:

$$EF = (C_i / C_{ref})\text{sample} / (C_i / C_{ref})\text{background} \tag{10}$$

EF: Enrichment Factor

C_i: activity of the studied radionuclide in bottom sediments (Bq/kg);

C_{ref}: activity of the reference element (Bq/kg) (in this study, ^{40}K was used as a geochemically stable element);

sample: the sampling point under study;

background**:** the background (reference) sampling point.

3. RESULTS AND DISCUSSION

3.1. Activity concentrations in water and bottom sediments

Globally, the mean gross alpha activity in natural waters ranges from 0.4 to 0.8 Bq/L. According to international studies, alpha activity levels of 0.4–0.5 Bq/L may indicate radiological anomalies (Li et al.2024). Gross alpha and beta activities are influenced by geological structure, mineral composition, and the intensity of anthropogenic activities (Ogundare et al.2015). The accurate selection of background reference sites is therefore critical in ecological and geochemical investigations (Islam et al.2015).

In the absence of historical baseline data for the study area, Lake Zhaksy–Zhangyztau, located approximately 16 km from the mining sites, was designated as the background (reference) water body. This lake is used as a drinking water source by residents of the Shantobe settlement. The radiological characteristics of surface water samples are presented in Table 1.

Table 1: Radiological characteristics of water samples, Bq/L .

Sampling location	**^{226}Ra**	**^{228}Ra**	**^{210}Po**	**^{210}Pb**	**^{234}U**	**^{238}U**	**Gross activity**	
							alpha	**beta**
Kutunguz River, Point 1	0.11±0.03	0.12±0.05	0.041± 0.018	0.035±0.027	0.071±0.018	0.04±0.011	0.2	0.27
Kutunguz River, Point 2	0.15±0.06	0.14±0.07	0.037± 0.012	0.065±0.033	0.222±0.042	0.139±0.027	0.67	0.39
Kutunguz River, Point 3	0.15±0.06	0.36±0.17	0.133± 0.045	0.014±0.005	0.448±0.073	0.371±0.059	1.81	0.79
Balkašin Quarry	0.22±0.04	1.54±0.31	0.026± 0.009	0.037±0.028	0.177±0.034	0.131±0.024	4.5	1.91
Lake Zhaksy–Zhalgyztau (Background)	0.11±0.03	0.13±0.05	0.028± 0.009	0.053±0.03	0.05±0.012	0.02±0.009	0.18	0.1

Data analysis demonstrated that gross alpha activity substantially exceeded gross beta activity across most sampling sites. Gross alpha and beta activities ranged from 0.18 to 4.5 Bq/L and from 0.1 to 1.91 Bq/L, respectively. In the Balkhashin quarry, gross alpha activity reached 4.5 Bq/L, while gross beta activity was 1.1 Bq/L.

Along the Kutunguz River, a progressive downstream increase in both gross alpha and beta activities was observed. At Point 1 (approximately 500 m upstream of the presumed mine water discharge), gross alpha and beta activities were 0.2 and 0.27 Bq/L, respectively. These values increased to 1.81 and 0.79 Bq/L at Point 3. Elevated activities in the Balkhashin quarry reflect radionuclide accumulation within this closed hydrological system.

According to the recommendations of the World Health Organization (World Health Organization, 2004), the guideline screening levels for gross alpha and gross beta activity in drinking water are 0.55 Bq/L and 1.0 Bq/L, respectively. In accordance with the sanitary regulations of the Republic of Kazakhstan (Ministry of Healthcare of the Republic of Kazakhstan, 2022), a more stringent level of 0.2 Bq/L is established for gross alpha activity, while the value of 1.0 Bq/L is retained for gross beta activity. Exceedance of these levels does not directly indicate non-compliance with radiation safety requirements but rather points to the need for further investigation. The final assessment is carried out based on an integral criterion that accounts for the cumulative contribution of individual radionuclides to the radiation dose. Taking these criteria into account, only point 1 on the Kutunguz River and the conditionally background site meet the screening requirements. At the remaining investigated sites, exceedances in gross alpha activity were recorded, whereas exceedance in gross beta activity was observed only in samples from the Balkashino quarry.

Radionuclide concentrations in the Kutunguz River were as follows:^{226}Ra — 0.11 ± 0.03 to 0.15 ± 0.06 Bq/L;^{228}Ra — 0.12 ± 0.05 to 0.36 ± 0.17 Bq/L;^{210}Po — 0.037 ± 0.012 to 0.133 ± 0.045 Bq/L;^{210}Pb — 0.014 ± 0.005 to 0.065 ± 0.033 Bq/L;^{234}U — 0.071 ± 0.018 to 0.448 ± 0.073 Bq/L;^{238}U — 0.04 ± 0.011 to 0.371 ± 0.059 Bq/L.

The specific activities of uranium isotopes (^{234}U and ^{238}U) at Points 2 and 3 of the Kutunguz River, as well as in the Balkhashin quarry, were markedly higher than background levels. At Point 3, ^{234}U (0.448 Bq/L) and ^{238}U (0.371 Bq/L) exceeded background values by approximately 8–10 times. At the same location, ^{210}Po activity was 4.8 times higher than background levels, whereas radium isotope activities remained close to background concentrations.

In the Balkhashin quarry, ^{228}Ra was the dominant radionuclide, with an activity of 1.54 Bq/L—more than 12 times higher than the background value. The average descending order of radionuclide concentrations was: Kutunguz River: ^{234}U > ^{238}U > ^{210}Po > ^{226}Ra > ^{228}Ra > ^{210}Pb, Balkhashin quarry: ^{228}Ra > ^{234}U > ^{238}U > ^{226}Ra > ^{210}Po > ^{210}Pb, Background site: ^{210}Pb > ^{234}U > ^{226}Ra > ^{228}Ra > ^{210}Po > ^{238}U (Fig. 3).

The principal contaminants of the Kutunguz River were identified as ^{234}U, ^{238}U, and ^{228}Ra, indicating contamination associated with the conserved Shantobe uranium mine. Although mean radionuclide concentrations exceeded background levels, they remained below guideline values established by the World Health Organization (World Health Organization. 2004). In contrast, ^{228}Ra activity in the Balkhashin quarry exceeded the WHO guideline level.

Comparative analysis with international studies conducted under analogous environmental conditions indicates that radionuclide concentrations in the Kutunguz River fall within ranges reported elsewhere (Bakhur.2008; Mohuba et al.2022; Duong et al.2021). The ^{228}Ra concentration in the Balkhashin quarry is also comparable to or lower than values documented in quarry lakes at uranium mining sites, where activities up to 57.7 Bq/L have been reported (Rodriguez et al.2024).

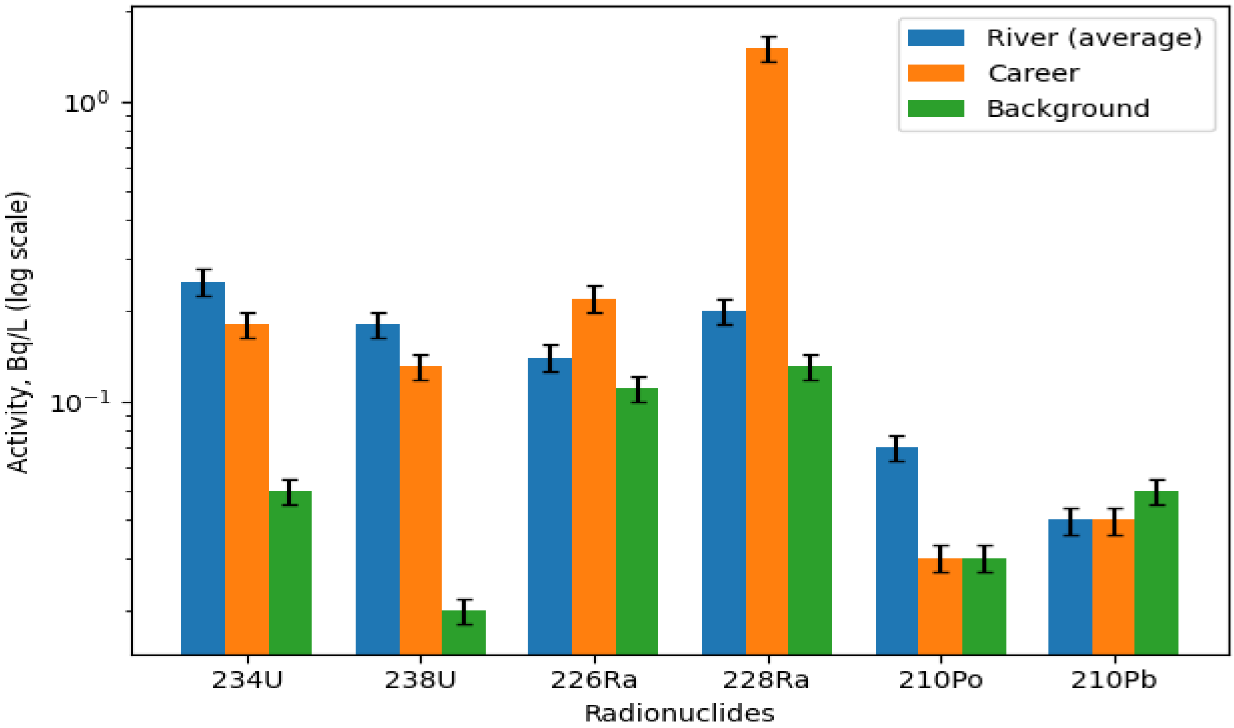

Fig. 3: Logarithmic distribution of radionuclide concentrations.

Table 2 presents radionuclide composition and gross alpha and beta activities in bottom sediments. The mean radionuclide concentrations decrease in the following order: $^{40}K > ^{226}Ra > ^{232}Th > ^{234}U > ^{238}U$. Compared with international reference levels, the average concentrations remain below globally recommended values.

Table 2: Radionuclide concentrations and specific effective activity in bottom sediments (0–15 cm layer, dry weight), Bq/kg

Sampling location	**^{226}Ra**	**^{232}Th**	**^{40}K**	**^{234}U**	**^{238}U**	**A_{eff}**
Kutunguz River, Point 1	37.53±5.88	38.68±5.39	454.3±100.5	9.8±2.8	7.8±2.2	128±12.83
Kutunguz River, Point 2	37.03±6.01	73.57±8.61	763±126.67	9.4±2.6	7.4±2.2	201±17.07
Kutunguz River, Point 3	26.85±4.8	41±5.39	474±95.65	21.6±4.8	14.4±3.2	123±12.05
Balkašin Quarry	209.03±22.3	62.83±8.52	828±147.67	164±24	144±20	365±28.23
Lake Zhaksy–Zhangyztau (Background)	38.57±6.35	83.1±9.61	829.67±136	14±3,8	12±2.8	221±18.6
Global average level	8–160	4–130	100–700	4–140	4–140	

The specific activities of ^{232}Th and ^{40}K in bottom sediments remained within established natural background ranges (38–83 Bq/kg and 454–830 Bq/kg, respectively). In the Kutunguz River, ^{232}Th activity varied from 38.68 ± 5.39 to 73.57 ± 8.61 Bq/kg (Table 2), whereas the background site at Lake Zhaksy–Zhangyztau exhibited a value of 83.1 ± 9.61 Bq/kg. The highest ^{40}K activity (829.67 ± 136 Bq/kg) was recorded at the background site.

The highest activity of ^{40}K (829.67 ± 136 Bq/kg) was recorded at the conditionally background site. This fact is not associated with uranium–radium mineralization and reflects the lithogenic characteristics of the studied territory. Unlike uranium and radium isotopes, ^{40}K is not an indicator of technogenic impact related to uranium mining, and its elevated concentrations are caused by natural geochemical variability of rocks. In this regard, the considered site should be interpreted as a local background primarily for radionuclides of the uranium series, whereas variations in ^{40}K content may reflect the natural heterogeneity of the geological environment and do not reduce its significance as a comparative reference within the framework of this research.

These findings are consistent with data reported for reclaimed uranium mining areas in other regions of Northern Kazakhstan. For example, radiometric investigations near the Grachevskoye uranium deposit and the settlement of Saumalkol documented ^{40}K activities ranging from 587 to 689 Bq/kg (Subbotin et al.2025). Overall, radionuclide activities in bottom sediments across the investigated sites are comparable to background values, with the exception of the Balkhashin quarry, where concentrations exceed local background levels but remain within global average ranges. The values measured in the Kutunguz River are broadly consistent with those reported for analogous environments worldwide (Table 3).

Table 3: Comparison of mean specific activities of ^{226}Ra, ^{232}Th, ^{40}K, and ^{238}U in bottom sediments with data from international studies, Bq/kg.

Country	**Location**	**^{226}Ra**	**^{232}Tr**	**^{40}K**	**^{238}U**	**Ref.**
Korea	Korean watershed	31.0	58.1	911	26.8	(Kang et al. 2024)
Egypt	Lake Nasser	14.47	17.83	95.34	30.94	(El-Shlemy et al. 2025)
China	Wei River	21.8	33.1	833	-	(Lu et al. 2007)
Algeria	Ain Dalia Dam	-	0.27	286.61	4.34	(Hamed et al. 2024)
Bangladesh	Karnaphuli	35.9	65.5	272	37.2	(Chowdhury et al. 1999)
Pakistan	Gilgit and Ind	50.7	70.2	532	-	(Qureshi et al. 2014)
Turkey	Southern coast of Turkey	-	9.0	157.7	-	(Özmen et al. 2014)
USA	Reedy River	21.4	45.3	609	37.8	(Powell et al. 2007)
Kazakhstan	Kutunguz River	33.80	51.08	563.7	9.8	This study

Note: – no data

3.2. Distribution coefficients (Kd) of radionuclides in bottom sediments and water

Bottom sediment samples were collected at the same points as the water samples, which made it possible to perform their comparative analysis. At all investigated sites, radionuclide concentrations in bottom sediments exceeded the corresponding values in the aqueous phase. The distribution coefficient (K_d), defined as the ratio of radionuclide activity in bottom sediments (Bq/kg) to their activity in water (Bq/L), varied within the ranges of 179–950 L/kg for ^{226}Ra, 42–926 L/kg for ^{234}U, and 39–1100 L/kg for ^{238}U.

The highest K_d values were recorded in the Balkashin quarry reservoir (up to ~950 L/kg), indicating a pronounced tendency for radionuclide accumulation in bottom sediments. At the same time, at points 2 and 3 of the Kutunguz River, K_d values for uranium remained relatively low (on the order of 40–50 L/kg), indicating its increased mobility in the aquatic environment.

The observed differences in K_d values may be associated with the hydrological characteristics of the studied systems. The Balkashin quarry reservoir represents a relatively closed system with limited water exchange, where conditions are formed for the local accumulation of radionuclides. In contrast, the Kutunguz River is characterized by a flowing regime, in which radionuclides, including uranium isotopes, may be transported downstream.

Differences in the behavior of uranium and radium isotopes in flowing and closed aquatic systems are likely caused by the combined influence of hydrogeochemical factors. Under riverine conditions, an oxidizing environment and the presence of carbonate compounds may promote the formation of soluble uranyl–carbonate complexes, leading to decreased K_d values and increased migration capacity of uranium. In closed water bodies, by contrast, longer water residence time and the presence of sorption surfaces, such as clay minerals and iron and manganese oxides, may contribute to the fixation of radionuclides in bottom sediments. It should be noted that within the framework of the present research, the distribution coefficient is used primarily as a tool for comparative analysis. Therefore, the obtained results should be regarded as a preliminary quantitative-descriptive assessment reflecting general trends in the migration behavior of radionuclides under the studied conditions.

3.3. Assessment of Radiological Risk

The calculated radiological indices indicate that, at most sampling locations (Kutunguz River points 1–3 and the background site), radiation levels correspond to those typical of natural landscapes described in reports of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR.2000).

The radium equivalent activity (Ra_eq) values ranged from 121.98 Bq/kg to 362.63 Bq/kg, with an average of 206.94 Bq/kg. All values are below the reference level of 370 Bq/kg recommended by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) (UNSCEAR.2000).

The absorbed gamma dose rate (ADR) varied from 56.93 to 169.05 nGy/h, with a mean of 96.32 nGy/h. This average exceeds the global mean background level of 60 nGy/h reported in the literature (Yi et al.2020). Along the Kutunguz River, ADR values were close to global averages, with a slight increase at the background site (103 nGy/h). However, a substantially elevated value (169 nGy/h), approximately three times the global average, was recorded at the Balkhashin quarry.

The annual effective dose equivalent (AEDE) ranged from 69.8 to 207 $\mu Sv\cdot yr^{-1}$, with a mean value of 118 $\mu Sv\cdot yr^{-1}$. These values generally fall within the typical global outdoor exposure range (0.07–0.13 $mSv\cdot yr^{-1}$) reported by UNSCEAR (UNSCEAR.2000). The mean value slightly exceeds the global reference level of 70 $\mu Sv\cdot yr^{-1}$; however, this reference represents an average natural background level rather than a regulatory limit. Importantly, all calculated AEDE values remain well below the public exposure limit of 1 $mSv\cdot yr^{-1}$ recommended by the International Commission on Radiological Protection (ICRP.1990). Therefore, the observed exposure levels can be considered within the range of natural variability and do not indicate a significant radiological health risk.

Both the internal (H_in) and external (H_ex) hazard indices for natural radiation should not exceed 1 mSv/year. In this study, the calculated average values ranged from H_ex = 0.33–0.98 and H_in = 0.40–1.54 (Fig. 4). Most samples comply with the permissible limits for radiation exposure. However, the sample from the Balkashin quarry approaches the threshold for the external index (H_ex = 0.98) and exceeds the internal index (H_in = 1.54), indicating a potential contribution from radon and its decay products if this material is used in enclosed spaces. The remaining sites fall within the safe radiation category and do not pose significant risk to the population. Particular attention should be given to the internal hazard index (H_in), the value of which in the Balkashino quarry exceeds unity (H_in = 1.54). This indicator reflects the potential impact of internal exposure pathways, primarily due to radon (^{222}Rn) and its decay products formed from ^{226}Ra. Under these conditions, the main exposure pathway is inhalation. When such materials are used in enclosed or poorly ventilated spaces, the accumulation of radon in air is possible, which may lead to an increased radiation dose to the respiratory system. Additional exposure pathways may include inhalation of dust particles and incidental ingestion of contaminated material. It should be noted that the exceedance of H_in is local in nature and is caused by the characteristics of a closed hydrological system that promotes radionuclide accumulation. At the remaining sites, index values do not exceed unity, indicating a low level of internal radiological risk. At the same time, within the framework of this study, direct measurements of radon exhalation were not performed, which should be taken into account in the interpretation of the results and in planning further researches.

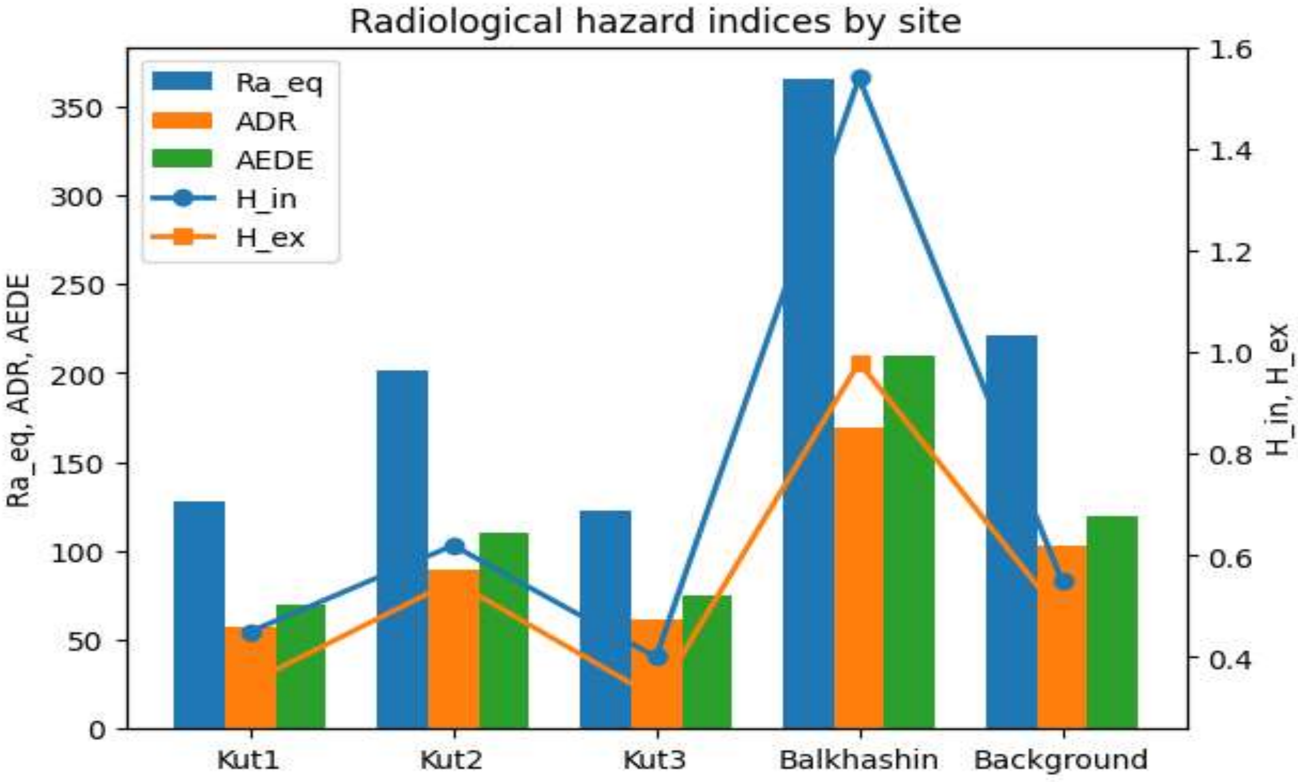

Fig. 4: Radiological hazard indices by sampling site.

At the background site (Lake Zhaksy–Zhangyztau), the committed effective dose (CED) due to water ingestion was estimated at 0.14 mSv·year⁻¹**.** The major contribution to the total dose is provided by radium isotopes (^{228}Ra and ^{226}Ra), followed by ^{210}Po and ^{210}Pb, while uranium isotopes contribute only marginally. The obtained value exceeds the World Health Organization (WHO) (World Health Organization.2004) drinking water screening reference level of 0.1 mSv·year⁻¹**,** but remains significantly below the public dose limit of 1 mSv·year⁻¹ recommended by the International Commission on Radiological Protection (ICRP.1990). It should be noted that the elevated value of CED at this site is not associated with technogenic impact but is likely caused by natural factors. Lake Zhaksy–Zhangyztau represents a weakly flowing hydrological system, in which processes of radionuclide accumulation in the water mass and bottom sediments, as well as their secondary mobilization, are possible. The lake is fed by the Karasu River only in spring and early summer, and is drained by the Akkanburlyk River. Additional influence may be exerted by the geochemical composition of the underlying rocks enriched in radium, which leads to its increased input into the aquatic environment.

3.4. Ecological Contamination Indices

The analysis of ecological pollution indices of bottom sediments—including the Contamination Factor (CF), Pollution Load Index (PLI), and Enrichment Factor (EF)—made it possible to identify spatial differences in radionuclide accumulation. It should be noted that these indices were originally developed for assessing contamination by heavy metals; therefore, their application to radionuclides is of a comparative nature and is aimed at identifying relative differences between sites rather than providing an absolute quantitative assessment of contamination.

The analysis of ecological contamination indices for bottom sediments—including the Contamination Factor (CF), Pollution Load Index (PLI), and Enrichment Factor (EF)—yielded the following results. Calculation of the Contamination Factor (CF) demonstrated that bottom sediments of the Kutunguz River at all investigated sampling sites are characterized by low or negligible levels of contamination. The CF values for ^{226}Ra, ^{232}Th, and ^{40}K do not exceed unity, indicating conformity with background conditions and the absence of significant radionuclide accumulation within the river channel system. These findings suggest that, despite the presence of external anthropogenic influences, the flowing hydrological regime effectively prevents long-term retention and accumulation of radionuclides in bottom sediments.

In contrast, bottom sediments of the Balkhashin quarry exhibit a distinctly different ecological pattern. A considerable level of contamination was recorded for ^{226}Ra (CF $\approx$ 5.4), indicating selective accumulation of radium isotopes in bottom sediments and underscoring the role of closed water bodies as local geochemical sinks for radionuclides.

The Pollution Load Index (PLI) further corroborates these observations. PLI values below unity (PLI $<$ 1) for all sampling points along the Kutunguz River indicate the absence of cumulative ecological loading and reflect a favorable ecological condition of bottom sediments. Conversely, exceedance of the threshold value at the Balkhashin quarry (PLI $\approx$ 1.6) reflects the integrated effect of radionuclide accumulation and supports classification of this site as ecologically impacted.

Analysis of the Enrichment Factor (EF) indicates that the distribution of ^{232}Th in all investigated sediments is primarily governed by natural lithogenic controls (EF $<$ 1). For ^{226}Ra, only weak or minor enrichment was observed in the bottom sediments of the Kutunguz River, whereas moderate anthropogenic enrichment was identified in the Balkhashin quarry (EF $\approx$ 5.4), clearly reflecting the influence of historical uranium mining activities.

Overall, the ecological indices reveal pronounced spatial differentiation in contamination patterns: the flowing sections of the Kutunguz River correspond to background conditions, whereas the Balkhashin quarry demonstrates technogenic accumulation of radionuclides, particularly ^{226}Ra. These results highlight the high diagnostic value of the combined application of CF, PLI, and EF indices for assessing the ecological condition of bottom sediments and confirm their effectiveness, in conjunction with radiological hazard indices, for identifying long-term environmental consequences of anthropogenic impacts in uranium mining regions. However, methodological limitations in the application of CF, PLI, and EF to radionuclides should also be taken into account:

1. EF is calculated using ^{40}K as a reference element, which exhibits natural variability between sites, thereby influencing enrichment values.
2. Radionuclides are subject to radioactive decay, migration, and sorption processes, which are not considered in the classical formulations of these indices.

In this regard, the obtained indicators should be regarded as comparative, reflecting relative differences between sites rather than absolute measures of contamination.

3.5. Cluster Analysis

Cluster analysis (CA) enables identification of groups of objects sharing similar characteristics within a multivariate dataset (Alkufi et al.2023). In the present study, hierarchical agglomerative clustering was performed using the Ward linkage method with Euclidean distance applied to standardized variables (Li et al.2024). Sampling sites were grouped according to radionuclide composition and radiological parameters, allowing identification of spatial patterns in the distribution of natural radionuclides across the study area. Due to the limited number of observation points (n = 5), the results of the analysis are exploratory in nature and are intended to identify general spatial patterns rather than to provide rigorous statistical conclusions.

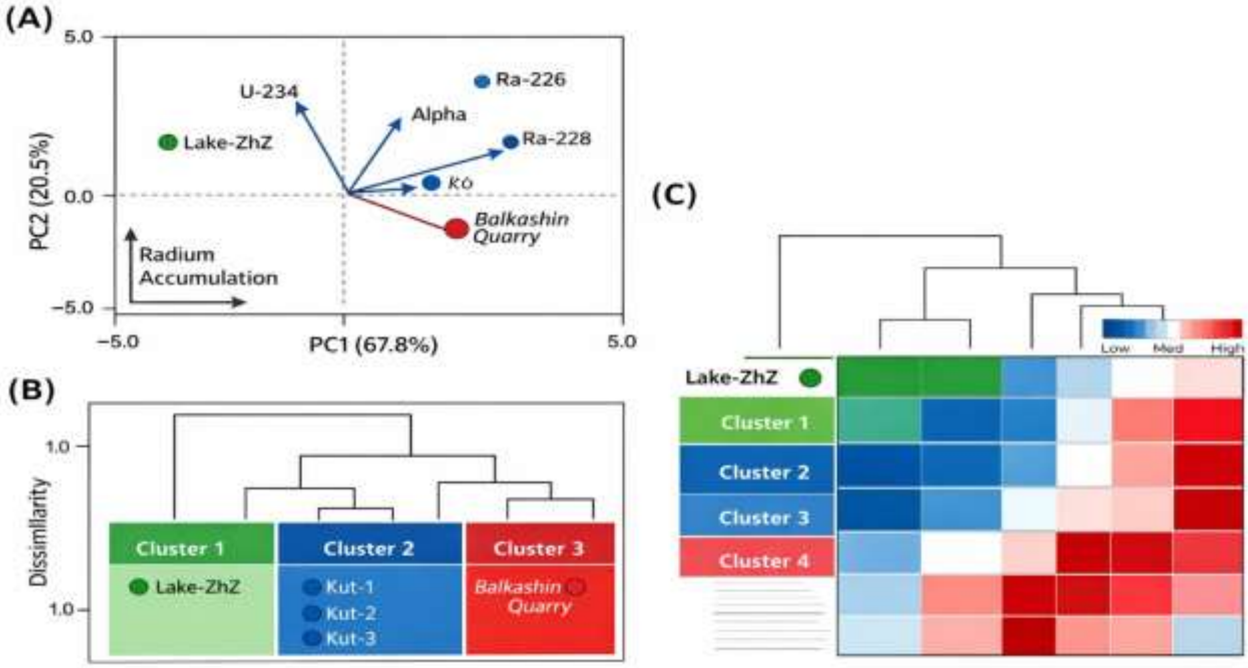

Fig. 5: Multivariate statistical analysis of the distribution of natural radionuclides at the investigated sampling sites: (A) principal component analysis (PCA), (B) hierarchical cluster analysis, (C) heatmap.

Cluster 1 includes the background reference site—Lake Zhaksy–Zhalgyztau (Lake-ZhZ). This site is characterized by low radiological indicators and minimal anthropogenic influence, confirming its suitability as a natural background control and reference location. In the principal component space (PCA; Fig. 5A), this sampling point exhibits weak association with radium and uranium vectors, reflecting the natural background conditions of the region.

Cluster 2 comprises samples collected from the Kutunguz River (Kut-1, Kut-2, Kut-3), forming a compact and internally consistent group. This clustering indicates similarity in hydrochemical conditions and radionuclide behavior along the river continuum. The results suggest the presence of a common geochemical control and a potential influence of the conserved Shantobe uranium deposit, manifested through radionuclide migration, redistribution within the aquatic environment, and increasing concentrations along the downstream flow direction.

Cluster 3 consists of a single isolated sampling site—the Balkhashin quarry. Its clear separation from both the background and river clusters reflects the specific hydrogeochemical conditions of this closed water body. The heatmap (Fig. 5C) demonstrates elevated levels of radium isotopes and gross alpha activity, indicating radionuclide accumulation under conditions of restricted water exchange. Such isolation suggests localized radiological enrichment and the potential development of an area with increased radiation load under prolonged exposure or hydrological disturbance.

Overall, the results confirm the spatial heterogeneity of radionuclide distribution within the study area. Flowing systems contribute to partial equalization of concentrations, whereas closed water bodies create conditions for local accumulation of radionuclides and the formation of zones with increased radiation load.

4. CONCLUSIONS

This research presents a radioecological assessment of the state of surface waters and bottom sediments in the zone of influence of reclaimed and conserved uranium mining facilities in Northern Kazakhstan. The obtained results indicate a redistribution of radionuclides within the river system, manifested by an increase in gross alpha and beta activity, as well as certain individual radionuclides, downstream along the Kutunguz River. The highest exceedances of background values were recorded at points 2–3, where the activities of uranium isotopes (^{234}U and ^{238}U) reached levels 8–10 times higher, indicating their migration with the water flow.

Elevated radionuclide concentrations in the Balkashin quarry reservoir, in particular the predominance of ^{228}Ra, reflect processes of their accumulation under conditions of a closed hydrological system. Analysis of distribution coefficients (K_d) demonstrated high mobility of uranium isotopes in the river system and their accumulation in bottom sediments under conditions of limited water exchange. At most sites, radiation exposure levels comply with international standards; however, in the area of the Balkashin quarry, local exceedances of dose indicators were identified.

For the background site—Lake Zhaksy–Zhalgyztau—the estimated effective dose from water consumption was 0.14 mSv/year, which slightly exceeds the WHO guideline level but remains below the permissible limit. The main contribution to the dose load is made by radium isotopes.

The obtained data indicate the need for further researches aimed at refining the mechanisms of radionuclide migration and require additional confirmation based on expanded observations and quantitative comparative analysis.

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REFERENCES

1. Akuo Ko, E.O., Otoo, F., Glover, E.T., Amponsem, E., Tettey Larbi, L., Ganbaatar, T., Csordás, A., Shahrokhi, A. and Kovács, T., 2025. Radiological implications of industrial activities on soil and water in artisanal gold-mining regions of Atiwa West. *Applied Sciences*, 15(18), 9857. https://doi.org/10.3390/app15189857
2. Alkufi, A.A., Kadhim, S.A., Alaboodi, A.S. and Alhous, S.F., 2023. Effects of natural radioactivity of some chemical and organic fertilizers on gonads in Iraqi Kufa markets. *Nature Environment Pollution Technology*, *22*, p.4. https://doi.org/10.46488/NEPT.2023.v22i04.030
3. Bakhur, A.E., 2008. Scientific and methodological foundations of radioecological assessment of the geological environment. PhD Thesis, Moscow, Russia. https://www.dissercat.com/content/nauchno-metodicheskie-osnovy-radioekologicheskoi-otsenki-geologicheskoi-sredy-0
4. Beretka, J. and Mathew, P.J., 1985. Natural radioactivity of building materials. *Health Physics*, 48(1), pp. 87–95. https://scholar.google.com/scholar?q=Natural+radioactivity+of+building+materials+Beretka+Mathew
5. Bessa, A.Z.E., Koutchouo, M.G., Doumo, E.P.E., Manishimwe, N.K., Tanantsap, R.J.N., Djoban, J.G.T., Bekonga Gouott, B.S. and Armstrong-Altrin, J.S., 2024. Assessment of heavy metals and radionuclides (U and Th) contamination, and source identification of the Lékié Watershed sediments, Cameroon. *Geosystems and Geoenvironment*, 3(1), 100249. https://doi.org/10.1016/j.geogeo.2023.100249
6. Bersimbaev, R.I. and Bulgakova, O., 2015. The health effects of radon and uranium in Kazakhstan. *Genes and Environment*, 37, 18. https://doi.org/10.1186/s41021-015-0019-3
7. Brzhanov, R.T., Sofronova, L.I. and Abramova, S.A., 2020. Analysis and technology to reduce the impact of tailings on the ecology of local water bodies. *IOP Conference Series: Materials Science and Engineering*, 962(4), 042063. https://doi.org/10.1088/1757-899X/962/4/042063
8. Chowdhury, M.I., Alam, M.N. and Hazari, S.K.S., 1999. Radionuclides in sediments and soils of Bangladesh. *Applied Radiation and Isotopes*, 51(6), pp. 747–755. https://doi.org/10.1016/S0969-8043(99)00098-6
9. Committee for Technical Regulation and Metrology of the Republic of Kazakhstan, 2006. ST RK 1545-2006. Radiation control. Sampling of surface and wastewater. Kazakhstan. [in Russian] https://prg.kz/Document/?doc_id=30527431
10. Duong, V.-H., Nguyen, T.-D., Hegedus, M., Kocsis, E. and Kovacs, T., 2021. Study of well waters from high-level natural radiation areas in northern Vietnam. *International Journal of Environmental Research and Public Health*, 18, 469. https://doi.org/10.3390/ijerph18020469
11. Dyussembayeva, M., Aidarkhanova, A., Tashekova, A., Shakenov, Y., Kolbin, V. and Merkel, A., 2025. Assessment of contamination of natural waters with radionuclides and heavy metals: the case of Karabulak Creek at the Semipalatinsk Test Site. *PLoS ONE*, 20(2), e0310833. https://doi.org/10.1371/journal.pone.0310833
12. El-Shlemy, E.S., Gad, A., El Feky, M.G., Mahmoud, A.-M.A., El-Sayed, O. and Abed, N.S., 2025. Potentially toxic elements and natural radioactivity in Nasser Lake sediments: Environmental risks in a key Egyptian freshwater lake. *Toxics*, 13(9), 745. https://doi.org/10.3390/toxics13090745
13. Galhardi, J.A., García-Tenorio, R., Bonotto, D.M., Francés, I.D. and Motta, J.G., 2017. Natural radionuclides in plants, soils and sediments affected by U-rich coal mining activities in Brazil. *Journal of Environmental Radioactivity*, 177, pp. 37–47. https://doi.org/10.1016/j.jenvrad.2017.06.001

14. GOST 17.1.5.01-80, 1980. Nature protection. Hydrosphere. General requirements for sampling bottom sediments of water bodies for pollution analysis. USSR. https://prg.kz/Document/?doc_id=37927607
15. Government of the Republic of Kazakhstan, 2001. On approval of the Program for the conservation of uranium mining enterprises and elimination of the consequences of uranium deposit development for 2001–2010, https://adilet.zan.kz/rus/docs/P010001006_
16. Hakanson, L., 1980. An ecological risk index for aquatic pollution control: a sedimentological approach. *Water Research*, 14(8), pp. 975–1001. https://doi.org/10.1016/0043-1354(80)90143-8
17. Hamed, Y., Ayadi, Y., Hadji, R., Ben Saad, A., Gentilucci, M. and Elaloui, E., 2024. Environmental radioactivity, ecotoxicology (^{238}U, ^{232}Th and ^{40}K) and potentially toxic elements in water and sediments from North Africa dams. *Sustainability*, 16(2), 490. https://doi.org/10.3390/su16020490
18. ICRP, 1990. Recommendations of the International Commission on Radiological Protection. ICRP Publication 60. Pergamon Press, Oxford, UK. https://www.icrp.org/publication.asp?id=icrp%20publication%2060
19. Idrisheva, Z., Ostolska, I., Skwarek, E., Daumova, G., Wiśniewska, M., Toktaganov, T. and Kozhakhmetov, Y., 2025. Evaluation of long-term environmental impact and radiological risks at a former thorium and rare earth site in north-eastern Kazakhstan. *Sustainability*, 17, 8569. https://doi.org/10.3390/su17198569
20. Islam, M.S., Ahmed, M.K., Raknuzzaman, M., Mamun, M.H.-A. and Islam, M.K., 2015. Heavy metal pollution in surface water and sediment: a preliminary assessment of an urban river in a developing country. *Ecological Indicators*, 48, pp. 282–291. https://doi.org/10.1016/j.ecolind.2014.08.016
21. Kamunda, C., Mathuthu, M. and Madhuku, M., 2016. An assessment of radiological hazards from gold mine tailings in Gauteng Province, South Africa. *International Journal of Environmental Research and Public Health*, 13, 138. https://doi.org/10.3390/ijerph13010138
22. Kang, T.-W., An, M., Han, Y.-U., Yang, H.J., Kang, T., Jung, S., Lee, W.-S. and Park, W.-P., 2024. Activity concentration of natural radionuclides in surface sediments of major river watersheds in Korea and assessment of radiological hazards. *Water*, 16(20), 2897. https://doi.org/10.3390/w16202897
23. Li, H., Wang, Q., Zhang, C., Su, W., Ma, Y., Zhong, Q., Xiao, E., Xia, F., Zheng, G. and Xiao, T., 2024. Geochemical distribution and environmental risks of radionuclides in soils and sediments runoff of a uranium mining area in South China. *Toxics*, 12(1), 95. https://doi.org/10.3390/toxics12010095
24. Lu, X., Zhang, X. and Wang, F., 2007. Natural radioactivity in sediment of Wei River, China. *Environmental Earth Sciences*, 53(7), pp. 1475–1481. https://doi.org/10.1007/s00254-007-0756-0
25. Ministry of Healthcare of the Republic of Kazakhstan, 2022. On the approval of hygienic standards for ensuring radiation safety. Order No. KR DSM-71, 2 August 2022. https://adilet.zan.kz
26. Mohuba, S.C., Abiye, T. and Nhleko, S., 2022. Evaluation of radionuclide levels in drinking water near gold mines and tailings. *Minerals*, 12, 1370. https://doi.org/10.3390/min12111370
27. Ogundare, F.O. and Adekoya, O.I., 2015. Gross alpha and beta radioactivity in soils and water around a steel processing facility. *Journal of Radiation Research and Applied Sciences*, 8(3), pp. 411–417. https://doi.org/10.1016/j.jrras.2015.02.009
28. Özmen, S.F., Cesur, A., Boztosun, I. and Yavuz, M.E., 2014. Radionuclides in beach sands of Turkey. *Radiation Physics and Chemistry*, 103, pp. 37–44. https://doi.org/10.1016/j.radphyschem.2014.05.034
29. Powell, B.A., Hughes, L.D., Soreefan, A.M., Falta, D., Wall, M. and DeVol, T.A., 2007. Elevated concentrations of primordial radionuclides in sediments from the Reedy River and surrounding creeks in Simpsonville, South Carolina. *Journal of Environmental Radioactivity*, 94(3), pp. 121–128. https://doi.org/10.1016/j.jenvrad.2006.12.013

30. Qureshi, A.A., Tariq, S., Din, K.U. and Manzoor, S., 2014. Evaluation of excessive lifetime cancer risk due to natural radioactivity in the river sediments of Northern Pakistan. *Journal of Radiation Research and Applied Sciences*, 7(4), pp. 438–447. https://doi.org/10.1016/j.jrras.2014.07.008
31. Raji, I.B., Hoffmann, E., Ngie, A. and Winde, F., 2021. Assessing uranium pollution levels in the Rietspruit River, South Africa. *International Journal of Environmental Research and Public Health*, 18, 8466. https://doi.org/10.3390/ijerph18168466
32. Rodriguez, V.G., Majumdar, A., Meza, I., Corcoran, L., Pierson, A., Gagnon, K., Cano, C., Ali, A.-M.S., Shuey, C.M., Jojola, G., Tan, W., Aprahamian, A., Cerrato, J.M. and Burns, P.C., 2024. Radiological analyses of ^{226}Ra and ^{238}U in surface water and sediments from the Jackpile Member of the Morrison Formation, Pueblo of Laguna, New Mexico. *Environmental Science & Technology*, 58(18), pp. 7879–7889. https://doi.org/10.1021/acs.est.4c01257
33. Saifulina, E., Janabayev, D., Kashkinbayev, Y., Shokabaeva, A., Ibrayeva, D. and Aumalikova, M., 2023. Epidemiology of somatic diseases near uranium mining enterprises in Kazakhstan. *Healthcare*, 11, 804. https://doi.org/10.3390/healthcare11060804
34. Severinenko, M.A., Solodukhin, V.P., Djenbaev, B.M., Lennik, S.G., Zholboldiev, B.T. and Snow, D.D., 2023. Occurrence of radionuclides and hazardous elements in the transboundary river basin Kyrgyzstan–Kazakhstan. *Water*, 15(9), 1759. https://doi.org/10.3390/w15091759
35. Subbotin, S., Krivitskiy, P., Larionova, N., Toporova, A., Kunduzbayeva, A., Turchenko, D., Tleukanova, Z. and Aidarkhanova, A., 2025. Assessment of the radiological situation near a mothballed uranium mining facility in North East Kazakhstan. *Scientific Reports*, 15, 16426. https://doi.org/10.1038/s41598-025-01697-6
36. UNSCEAR, 2000. Sources, Effects and Risks of Ionizing Radiation. United Nations, New York, USA. https://www.unscear.org/unscear/en/publications/2000_1.html
37. World Health Organization, 2004. Guidelines for Drinking-Water Quality. WHO, Geneva, Switzerland. https://iris.who.int/server/api/core/bitstreams/b437749a-43f7-472f-a6d9-42596e8ac0ae/content
38. Wu, Y., Wang, Y. and Xie, X., 2014. Occurrence, behavior and distribution of high levels of uranium in shallow groundwater at Datong Basin, China. *Science of the Total Environment*, 472, pp. 809–817. https://doi.org/10.1016/j.scitotenv.2013.11.109
39. Yi, L., Gao, B., Liu, H., Zhang, Y., Du, C. and Li, Y., 2020. Characteristics and assessment of toxic metal contamination in surface water and sediments near a uranium mining area. *International Journal of Environmental Research and Public Health*, 17(2), 548. https://doi.org/10.3390/ijerph17020548
40. Zhumadilov, K., Ivannikov, A. & Kassymzhanov, M., 2025. Radiation doses of population near uranium mines (EPR spectroscopy). *SSRN Electronic Journal*. https://doi.org/10.1016/j.envc.2025.101098