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Radioecological state of the environment in the area of the former Semipalatinsk Nuclear Test Site

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Abstract. Radioactive contamination of the environment in the former Semipalatinsk nuclear test site (Kazakhstan) is caused by the deposition and long-term retention of long-lived radionuclides in soil, water and vegetation, which poses potential risks to ecosystems and public health. The study aimed to assess the levels of contamination of soil, water and vegetation with americium-241, cesium-137 and plutonium-239/240 radionuclides in areas of different radiation risk in the former Semipalatinsk nuclear

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test site. Radiation and environmental monitoring were conducted at 12 control points using spectrometric analysis to determine the specific activity of the specified radionuclides in environmental samples. The study revealed pronounced differences in the content of radionuclides in soil, water and vegetation in areas with different levels of radiation risk. The maximum concentrations of americium-241 (0.55 ± 0.03 Bq/kg), cesium-137 (1.83 ± 0.15 Bq/kg) and plutonium-239/240 (0.012 ± 0.0015 Bq/kg) were recorded in the extreme radiation risk zone, while in the least contaminated areas, their levels were 4-7 times lower. In water bodies, the highest activity was recorded for cesium-137, with a concentration of 5.22 ± 0.2 Bq/l, which significantly exceeds the permissible limits. Significant accumulation of all three radionuclides was detected in the vegetation: Am-241 to 1.6 ± 0.3 Bq/kg, Cs-137 to 2.2 ± 0.1 Bq/kg, Pu-239/240 to 0.9 ± 0.1 Bq/kg. The highest levels were recorded in areas of extreme and maximum risk, mainly in pasture cereals. The analysis of the vertical distribution of radionuclides showed their differentiation by depth: Cs-137 and Am-241 were concentrated in the upper soil layer (0-10 cm), while Pu-239/240 partially migrated to 15-20 cm, which confirmed the risk of their inclusion in the trophic chains and the need for further monitoring. The data obtained can be used to plan measures for the environmental remediation of contaminated areas, regulate the agricultural use of pastures and ensure the radiation safety of the population

Keywords: radiation contamination; americium-241; cesium-137; plutonium-239/240; soil; water; vegetation

INTRODUCTION

Radioactive contamination of the environment in the former Semipalatinsk nuclear test site is a long-term environmental problem associated with a high level of accumulation of artificial radionuclides in soil, water bodies and vegetation. As a result of more than 450 nuclear tests conducted between 1949 and 1989, the site released long-lived radionuclides such as cesium-137, strontium-90, and plutonium-239 into the environment (Akhmetova *et al.*, 2024). These substances persist in ecosystems for decades, exerting radiotoxic effects and participating in migration processes in natural environments. The ability of radionuclides to penetrate ground and surface waters, accumulate in plant tissues and enter the food chain is of particular danger, as when they enter the human or animal body with drinking water or food, they are absorbed through the gastrointestinal tract, accumulate in tissues (especially in bone, muscle and parenchymal organs) and have chronic radiotoxic effects at the cellular and genetic levels, which may pose a threat to the biota and health of the population of nearby regions (Ongayev *et al.*, 2024).

Research in the field of radiation ecology, supported by international organisations, has contributed to the creation of radioactive contamination monitoring systems in the affected regions. The International Atomic Energy Agency (2014) and the European Commission (n.d.) have repeatedly initiated projects to assess the consequences of nuclear tests and develop methods for decontamination of contaminated areas. The contribution of the United Nations (2015) and World Health Organization (n.d.) programmes was to conduct epidemiological studies aimed at investigating the impact of radiation on public health. The analysis of the radioecological situation in the Semipalatinsk nuclear test site area covers a wide range of studies aimed at investigating the consequences of nuclear tests and their impact on the environment and public health. The impact of nuclear tests on the ecosystem of the region is manifested in the significant accumulation of radionuclides in soil and water, which was revealed by R. Akhmetova *et al.* (2024) in the absence of data on the transformation of radionuclides in food chains and mechanisms of their biological absorption. Historical changes in the radioecological situation, including the dynamics of radionuclide migration and distribution in natural environments, are considered in A. Mamyrbekov *et al.* (2024) without a comprehensive assessment of the current radiation background and interaction with agricultural ecosystems.

A generalised analysis of radioactive contamination management methods in different natural environments was presented in a review by A. Adeola *et al.* (2023). The review did not highlight the need for technological optimisation of monitoring and remediation. At the same time, they did not study the regional specifics of post-nuclear territories and did not consider the behaviour of americium-241, cesium-137 and plutonium-239/240 in agricultural landscapes with localised sources of contamination. D. Tchorz-Trzeciakiewicz *et al.* (2023) described seasonal fluctuations in the natural radiation background and concentrations of natural radionuclides in different ecosystems. However, the study did not compare the results of the study with man-made contamination sites and did not consider scenarios of interaction between natural and artificial radionuclides typical of nuclear test areas.

The impact of radioactive contamination on the health of the population living near the landfill is correlated with the nature of migration and accumulation of radionuclides in the natural environment (Işık *et al.*, 2024). S. Abd El-Azeem and H. Mansour (2021) analysed the content of natural radionuclides in soil samples with a focus on mineral composition and geochemical characteristics. However, the study does not cover anthropogenic radionuclides such as Cs-137 and Pu-239/240 and does not consider their environmental behaviour under conditions of nuclear contamination, which limits the applicability of the results in the context of assessing the radioecological state of former landfills. A. Panitskiy *et al.* (2022) highlighted the vertical distribution of radionuclides in the soil of the Semipalatinsk test site and provided relevant quantitative data. However, the authors do not consider the bioavailability of radionuclides, incorporation into food chains and transfer to aquatic and vegetation components of ecosystems. Furthermore, S.Zh. Sapanov *et al.* (2021) described soil contamination with radionuclides and heavy metals, but there is no analysis of the impact of this contamination on crops and livestock products, which limits the ecological and agricultural interpretation of the results.

The accumulation of radionuclides in vegetation was confirmed by N. Larionova *et al.* (2024), recording high concentrations of tritium in the landfill ecosystems, while other radionuclides with high radiotoxicity, such as Cs-137 and Pu-239/240, were not addressed, which reduced the accuracy of the environmental assessment. Similar results were reported by Y. Polivkina *et al.* (2024), describing the uptake of tritium by crops against the background of atmospheric pollution, although aspects of food safety and the physiological state of plants under chronic radiation exposure were not considered. The results of a study by D. Feng *et al.* (2022) on a comparison of the distribution of plutonium isotopes in soils from the Semipalatinsk test site and the Chinese Lob Nor site characterised migration processes in a geochemical context, but the biological behaviour of isotopes and their participation in trophic relationships remained outside the scope of the analysis.

Despite a considerable amount of research, several aspects of the radioecological state of the Semipalatinsk nuclear test site remain insufficiently studied. A detailed analysis of radionuclide migration in soil and water systems, their accumulation in vegetation and their impact on crops, as well as an assessment of the impact of contamination on the hydrological regime and bioremediation potential, is required. The study aimed to assess the radioecological state of the environment in the former Semipalatinsk nuclear test site with a focus on the contamination of soil, water sources and vegetation.

MATERIALS AND METHODS

The study was conducted in the laboratory of the Veterinary Department and the Agrotechnopark of Shakarim University (Kazakhstan) in July 2024, which addressed the seasonal features of radionuclide migration and accumulation in natural environments. To assess the radioecological situation, the territories adjacent to the Semipalatinsk nuclear test site were selected incorporating differences in radiation risk levels. The selection criteria were based on radiation mapping data for the region, the spatial distribution of gamma background, and historical information on nuclear test zones. The selection of sites was based on radiation risk levels, natural and landscape conditions, population density and logistical accessibility of the facilities. In the Abai district, where the radiation risk was suspected to be high, samples were taken in the settlements of Yer Zhanybek, Kulzhan ata and Baishuak. In Zhanasemey district, the areas around Kainar, Abyraly and Akbulak were surveyed, with the highest level of risk. For Ayagoz district, which is a high-risk area, the villages of Rustem, Bayan and Zhanat were selected. In Urdzhar district, where radiation exposure is minimal, the villages of Akan, Adilet and Maksat were selected. A total of twelve stationary control points were operated within the study, three in each district. At these points, soil, water and vegetation samples were collected, followed by spectrometric analysis to assess the levels of radionuclide contamination.

The analysis was conducted to determine the spatial distribution of radionuclides and their migration in various natural environments. Particular attention was paid to the study of the content of americium-241 (Am-241), cesium-137 (Cs-137) and plutonium-239/240 (Pu-239/240) in the samples, which ensured an objective assessment of the radioecological state of the region. The results obtained were compared with the permissible values established following the recommendations of the International Atomic Energy Agency (2014), which are used in radiation practice in the Republic of Kazakhstan as a member state of the Convention on Nuclear Safety and the Basic Safety Standards. Maximum permissible levels of specific activity in soil are: 0.3 Bq/kg for Am-241, 0.6 Bq/kg for Cs-137 and 0.02 Bq/kg for Pu-239/240. In the water environment, the maximum permissible concentrations are 0.2, 2 and 0.005 Bq/l, respectively. For plant samples, the indicative standards are up to 1 Bq/kg for Am-241, up to 0.6 Bq/kg for Cs-137 and up to 0.1 Bq/kg for Pu-239/240. These values were used as thresholds for interpretation of the results and classification of the surveyed areas by radiation risk levels. To increase the reliability of measurements, each pooled sample was analysed in triplicate. Since the original repeat measurement protocols were not available, the standard deviation (SD) values were estimated a priori based on the acceptable range of variability of the atomic emission spectrometry method, incorporating the sensitivity of the instrument at low concentrations. Estimated SDs were used in the tables as approximate indicators of data scatter.

Soil sampling was conducted based on the "envelope" methodology, which involves combining samples from five points in each study area into one mixed sample. The soil layer was sampled from a depth of 0-10 cm from the surface, which corresponds to the upper horizon most susceptible to the accumulation of radionuclides such as Cs-137 and Am-241. To assess the migration behaviour of plutonium, additional samples were taken from a depth of 10-20 cm, which identified a tendency of Pu-239/240 to be distributed at a deeper level. The weight of one combined sample was about 1 kg. The preparation of soil samples included transferring samples to plastic trays, removing impurities, grinding to 1-2 mm particles in a porcelain mortar and bringing them to an air-dry state. The samples were then dried in an oven at 105°C for 3 hours and sieved through a 1-2 mm mesh sieve. Decomposition of the samples was carried out by adding 20 ml of 3% nitric acid solution and stirring on a LIOP LS120 shaker (Russia) for 60 minutes. The resulting filtrate was diluted 50 times with distilled water and analysed by atomic emission spectrometry using an EXPEC 6500 spectrometer (China) (International Atomic Energy Agency, 2010). The concentration of the element was calculated by the formula (1):

$$C = \frac{a \times 50}{2 \times 1{,}000}, \quad (1)$$

where C – concentration of the element, mg/g; a – value of the element concentration displayed by the device, mg/l; 50 – volume of the extract, ml; 2 – mass of the sample, g; 1,000 – conversion factor for converting mass from millilitres to litres.

Water samples were collected from open water bodies, wells and springs using plastic containers to prevent secondary contamination. The samples were taken from the surface water layer (1-10 cm) in a volume of 1,000 ml, with all data recorded in a field passport. Before analysis, the samples were filtered through a paper filter and then diluted 50 times with distilled water. To avoid contamination of the samples, glass and polyethene containers were prepared and washed with Komarovsky's mixture and deionised water acidified with extra pure nitric acid ("ос. ч"). After preparation, the samples were analysed by atomic emission and mass spectrometry EXPEC 6500. The concentration of the element in the water sample was calculated using formula (2):

$$C = \frac{a \times 50}{1 \times 1{,}000}, \quad (2)$$

where 1 – mass of the attachment.

Vegetation and forage samples were collected in triplicate on 1×1 m plots. All vegetation was cut off with scissors within the plot boundaries, with the bottom cut left at least 3 cm from the soil surface. In the pastures, the mowing method was used to simulate grass eating by cattle, cutting short grasses at a height of 10-15 cm and tall grasses at 20-25 cm. Samples weighing 1.5-2 kg were packed in thick paper, plastic bags or paper bags. Before analysis, the samples were dried at 60-65°C in an oven, chopped with scissors (5-8 mm sections) and additionally ground in an electric grinder (2-5 minutes). A 2 g sample was isolated in a muffle furnace at 650°C for 3 hours, then the ash residue was decomposed with 2 ml of concentrated extra pure nitric acid, diluted 50 times with distilled water, and analysed using an EXPEC 6500 spectrometer. The element concentration was determined using formula (1).

The gamma radiation dose rate, as well as beta and alpha particle flux density, were determined following the Order of the Minister of Finance of the Republic of Kazakhstan No. 121 (2018) and Order of the Minister of Health of the Republic of Kazakhstan No. KR DSM-71 (2022). Measurements of gamma radiation exposure dose rate (EDR) were conducted in an open area at a height of 1 m from the soil surface using an RKS-01-SOLO radiometer (Russia), which ensured an objective assessment of the external radiation background of the studied areas. The flux density of alpha and beta particles was determined by the contact method on the soil surface using the Manufacturer: ATOMTEX, with a probe area of 1 cm^2, which provided a reliable assessment of the degree of soil contamination. To measure the volumetric activity of radon and thoron, a radon monitor Manufacturer: SOLO LLP (Republic of Kazakhstan)was used, which is used for sanitary and hygienic surveys of premises and territories.

To analyse the differences between groups of samples taken in areas with different levels of radiation risk, the methods of analysis of variance for multiple comparisons and Student's t-test for pairwise comparisons were used. In cases of non-normality of the data distribution, the non-parametric Mann-Whitney test was used. The level of statistical significance for comparisons between zones was set at $p < 0.05$. Statistical data processing was performed using IBM SPSS Statistics 26.0 software, which ensured the accuracy of calculations and the ability to visualise data. The study was conducted following international standards of bioethics and radiation safety (International Atomic Energy Agency, n.d.), as well as in compliance with the Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1975). In the course of the work, measures were taken to minimise environmental impact and ensure personnel safety.

RESULTS

Radiometric monitoring of the surveyed areas. The analysis of gamma radiation EDR demonstrated a significant variation in the radiation background depending on the studied areas. The maximum values were observed in extreme radiation risk (Yer Zhanybek, Kulzhan ata, Baishuak), where the EDR reached 0.32-0.33 μSv/h. This was significantly higher than the natural radiation background typical for uncontaminated areas, which averages 0.07-0.15 μSv/h. In the zone of maximum radiation risk (Kainar, Abyraly, Akbulak), the EDR level was in the range of 0.15-0.2 μSv/h, which also exceeded the upper limit of the background range, although it was lower than in the extreme risk zone. In the areas with increased and minimal risk (Rustem, Bayan, Zhanat, Akan, Adilet, Maksat), the EDR ranged from 0.07 to 0.15 μSv/h, which corresponded to the natural radiation background. The results are shown in Figure 1.

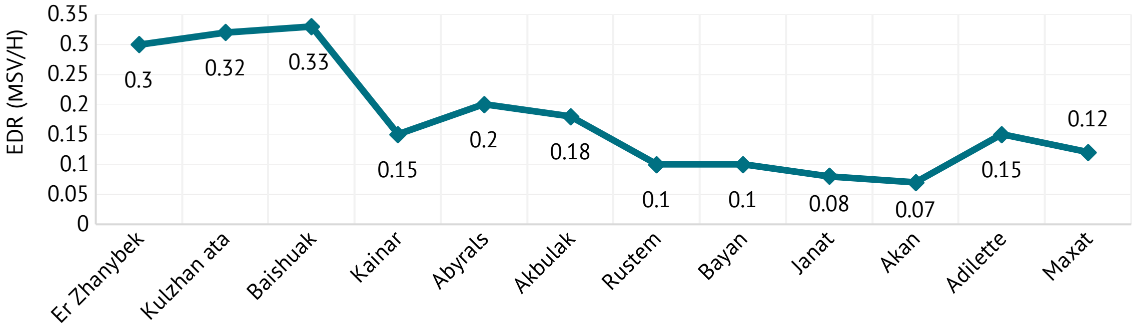

Figure 1*. Gamma radiation EDR at a height of 1 m from the soil surface at the studied points*
Source: *compiled by the authors*

The spatial distribution of EDR demonstrates pronounced fluctuations in the radiation background between areas with different degrees of contamination. The maximum values are recorded in areas historically exposed to the most intense radioactive impact, which confirms the presence of residual contamination. At the same time, a decrease in EDR levels at certain points may indicate the processes of natural decay of radionuclides and their migration deep into the soil profile. The flux density of alpha particles in the studied locations ranged from 0.2 to 2.2 ppm*cm^2. The highest values were registered in the extreme radiation risk zone (Er Zhanybek, Kulzhan ata, Baishuak), where the indicator reached 2.1-2.2 ppm*cm^2. High levels of alpha radiation may indicate the presence of transuranic elements, such as plutonium-239/240. In the zone of maximum radiation risk (Kainar, Abyraly, Akbulak), a sharp decrease to 0.2 ppm*cm^2 is observed, which may be due to the heterogeneity of alpha-emitting radionuclides in the soil. In the zone of increased radiation risk (Rustem, Bayan, Zhanat), the alpha particle flux density varies between 0.4-1.5 ppm*cm^2, while in the zone of minimal radiation risk (Akan, Adilet, Maksat) the lowest values are observed, not exceeding 0.3 ppm*cm^2. These values are significantly higher than the natural radiation background for uncontaminated areas, which is 0.1-0.2 ppm*cm^2 (Fig. 2).

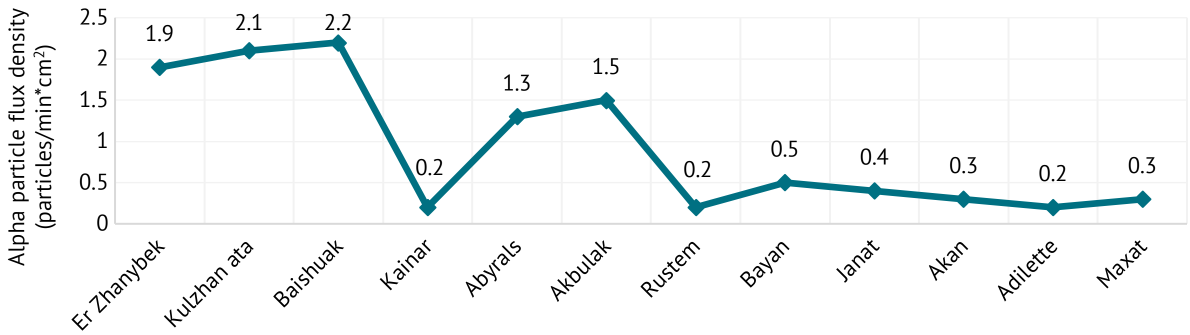

Figure 2*. Alpha particle flux density was measured on the soil surface at the studied points*
Source: *compiled by the authors based on International Atomic Energy Agency (n.d.)*

The analysis results show that alpha radiation levels are unevenly distributed over the territory, which may be due to different degrees of transuranic element migration in the soil profile. High values at certain points may indicate local areas of radioactive particle accumulation, which requires additional study of the geochemical features of the soil. In the settlements of Akan, Adilet, Maksat (Urdzhar district), Rustem (Ayagoz district) and Kaynar (Abay district), the flux density of alpha particles was 0.2-0.3 particles/min*cm^2, which corresponded to or only slightly exceeded the estimated values of the natural radiation background for uncontaminated areas.

According to radiation and hygiene standards, the flux density of beta particles in uncontaminated areas is no more than 2-2.5 ppm*cm^2, therefore the values can be used as a conditional background for assessing the man-made load. The range of 3.5-8.2 ppm/min*cm^2 was recorded in the studied areas, which reflects the presence of artificial radionuclides, in particular Cs-137 and Sr-90. The highest values were recorded in the zone of maximum radiation risk (Akbulak, Abyraly), where the flux density reaches 8-8.2 ppm*cm^2. In the extreme radiation risk zone (Er Zhanybek, Kulzhan ata, Baishuak), moderately high values (4.2-5.2 ppm*cm^2) are observed, indicating the presence of residual contamination. In the zone of increased radiation risk (Rustem, Bayan, Zhanat), the values decrease to 3.5-4 ppm*cm^2, while in the zone of minimal radiation risk (Akan, Adilet, Maksat), the beta particle flux density increases to 5.6 ppm*cm^2, which may be due to local redistribution of radionuclides due to natural and anthropogenic factors (Fig. 3).

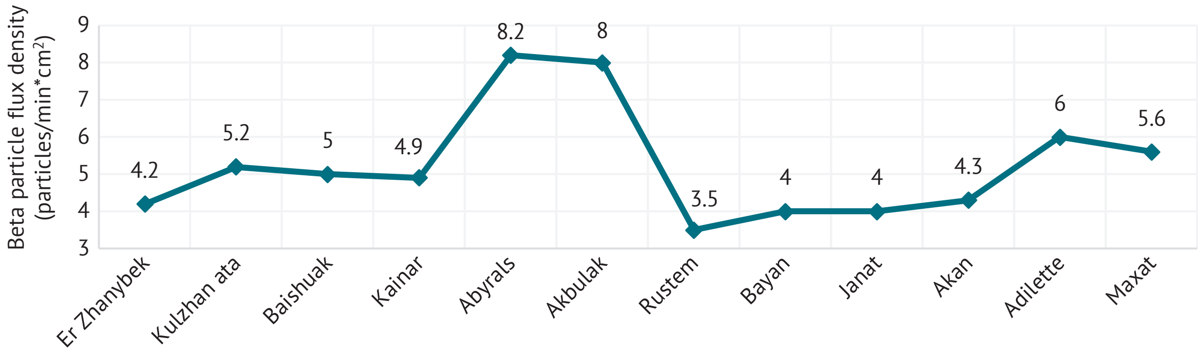

***Figure 3**. Beta-particle flux density at the studied points*

***Source:** compiled by the authors*

The graph demonstrates a significant variation in the beta particle flux density in the studied areas, which may indicate heterogeneity of radionuclide distribution in the soil. In some areas with low overall background radiation levels, such as the Ayagoz region (Rustem – 3.5 ppm*cm^2; Bayan and Zhanat – 4 ppm*cm^2 each), local increases in beta radiation density were observed compared to alpha background, which may indicate migration of radionuclides or their fixation in certain types of soil sediments. In addition, the identified differences may be due to natural processes of pollutant redistribution, such as wind and water erosion.

The obtained radiometric monitoring data confirm the heterogeneity of radioactive contamination in the studied areas, which is associated with historical nuclear tests and subsequent radionuclide migration processes. Maximum levels of gamma radiation, as well as increased density of alpha and beta particle fluxes, were recorded in the areas of emergency and maximum radiation risk (Abay and Zhanasemey districts), which indicates high residual activity of radionuclides. At the same time, local deviations detected in the areas classified as zones of relatively minimal radiation risk (Urdzhar district), according to radiation mapping data, background measurements of EDR and radionuclide activity, may be related to natural processes of redistribution of pollutants and require additional study.

Radioactive contamination of soil and spatial distribution of radionuclides. The study of radioactive contamination of soil in the Semipalatinsk nuclear test site made it possible to determine the content and spatial distribution of radionuclides with different lifetimes, including long-lived (Am-241, Pu-239/240) and intermediate-lived Cs-137. The values of these isotopes were determined by alpha and gamma spectrometry using an EXPEC 6500 analyser (sampling was carried out at a depth of 0-10 cm). The concentrations of radionuclides in soil samples varied depending on the level of radiation risk in the study areas. The highest levels of specific activity of radionuclides were observed in the Abay and Zhanasemey districts, which were classified as zones of high and extreme radioactive contamination based on radiation mapping and exceeding the thresholds set by the International Atomic Energy Agency. This is probably due to their primary deposition during nuclear tests and subsequent migration in the soil profile.

The results of alpha and gamma spectrometric analysis of the soil showed that in extreme radiation risk (Yer Zhanybek, Kulzhan ata, Baishuak), Am-241 concentrations were in the range of 0.52-0.55 Bq/kg, Cs-137 1.78-1.83 Bq/kg, and Pu-239/240 0.011-0.012 Bq/kg. Comparison of these values with the permissible levels set by the International Atomic Energy Agency, according to which the maximum permissible specific activity in soil is 0.3 Bq/kg for Am-241, 0.6 Bq/kg for Cs-137, and 0.02 Bq/kg for Pu-239/240, highlighted the following. The concentrations of Am-241 exceed the normative values by 1.7-1.8 times, Cs-137 by 3-3.1 times, while Pu-239/240 remains within the permissible range (Table 1). The data were calculated according to formula (1).

***Table 1**. Specific activity of radionuclides in soil (Bq/kg)*

Settlement	Am-241	Cs-137	Pu-239/240
Er Zhanybek	0.55 ± 0.03	1.83 ± 0.15	0.012 ± 0.0015
Kulzhan ata	0.52 ± 0.03	1.78 ± 0.12	0.012 ± 0.001
Baishuak	0.53 ± 0.04	1.8 ± 0.1	0.011 ± 0.0012

Table 1. Continued

Settlement	Am-241	Cs-137	Pu-239/240
Kainar	0.48 ± 0.03	0.8 ± 0.06	0.009 ± 0.001
Abyrals	0.49 ± 0.04	0.85 ± 0.07	0.008 ± 0.001
Akbulak	0.5 ± 0.04	0.87 ± 0.06	0.009 ± 0.001
Rustem	0.3 ± 0.02	0.5 ± 0.04	0.005 ± 0.001
Bayan	0.3 ± 0.02	0.4 ± 0.03	0.005 ± 0.001
Janat	0.3 ± 0.02	0.5 ± 0.04	0.005 ± 0.001
Akan	0.25 ± 0.02	0.22 ± 0.02	0.001 ± 0.0005
Adilette	0.24 ± 0.01	0.2 ± 0.02	0.001 ± 0.0005
Maxat	0.25 ± 0.02	0.19 ± 0.02	0.001 ± 0.0005

Note: *values are given as arithmetic means ± SD estimates calculated based on triplicate analysis of each pooled sample. SDs are estimated within the typical accuracy limits of the atomic emission spectrometry method (EXPEC 6500)*
Source: *compiled by the authors*

The spatial distribution of radionuclides in the soil of the studied areas demonstrates regularities caused by the history of nuclear tests and subsequent geochemical processes. In the most contaminated areas, a stable retention of Am-241 is observed, which confirms its low migration capacity in the soil profile. Cs-137, on the contrary, shows more pronounced concentration variations, which may be due to its tendency to secondary redistribution and partial leaching. Pu-239/240 was detected in trace amounts in all areas studied, which corresponds to its low mobility and high sorption capacity for soil particles. These features indicate the need for continued monitoring to identify potential risks of long-term contamination and assess the dynamics of radionuclide migration.

To assess the spatial distribution of radionuclides, an analysis of the vertical soil profile was also conducted. The data show that most of the Cs-137 and Am-241 are concentrated in the upper soil layers (0-10 cm), while Pu-239/240 tends to migrate deeper, with concentrations detected at depths of up to 15-20 cm. This is explained by its high affinity for soil particles, its ability to be sorbed by organo-mineral complexes, and its low solubility in water. In areas with low levels of radiation contamination (Akan, Adilet, Maksat), radionuclide concentrations are significantly lower: Am-241 0.24-0.25 Bq/kg, Cs-137 0.19-0.22 Bq/kg, Pu-239/240 0.001 Bq/kg. The results of the soil sample analysis confirm a significant accumulation of radionuclides in the study areas, especially in the areas of emergency and maximum radiation risk. The bulk of radionuclides is concentrated in the upper soil layer, but some Cs-137 demonstrates the ability to migrate, which requires further monitoring.

Radionuclide content in water bodies. Radioactive contamination of water bodies reflects the migration of radionuclides into the environment. Water contributes to the transport of radioactive particles, which can lead to their accumulation in hydrosystems and further spread in ecosystems. During the study, water samples were collected and analysed from various sources, including open water bodies, wells and springs located in areas with different levels of radiation risk. Radionuclide concentrations in the water environment were analysed using an EXPEC 6500 atomic emission and mass spectrometer, which provides high sensitivity in determining trace amounts of Am-241, Cs-137 and Pu-239/240. The study determined that the levels of these radionuclides differed significantly depending on the location of water sources and the degree of radiation risk in the respective territories. The maximum concentrations of radionuclides were recorded in the extreme radiation risk zone, which may indicate the continued intake of pollutants from the soil layer. In the zone of maximum radiation risk, a slight decrease in radionuclide content was noted, which may be due to the processes of dilution and self-purification of water bodies. In the zones of increased and minimum radiation risk, radionuclide concentrations are reduced, indicating lower mobility and natural sorption processes on bottom sediments (Table 2). The data were calculated according to formula (2).

***Table 2**. Radionuclide content in water samples (Bq/l)*

Settlement	Am-241	Cs-137	Pu-239/240
Er Zhanybek	0.5 ± 0.04	5.22 ± 0.2	0.1 ± 0.01
Kulzhan ata	0.3 ± 0.03	4.92 ± 0.12	0.09 ± 0.008
Baishuak	0.4 ± 0.03	5.1 ± 0.08	0.1 ± 0.009
Kainar	0.45 ± 0.04	4.88 ± 0.1	0.09 ± 0.01
Abyrals	0.44 ± 0.04	4.72 ± 0.15	0.07 ± 0.006
Akbulak	0.45 ± 0.04	4.85 ± 0.13	0.09 ± 0.009
Rustem	0.38 ± 0.03	3.76 ± 0.08	0.08 ± 0.009

Table 2. Continued

Settlement	Am-241	Cs-137	Pu-239/240
Bayan	0.34 ± 0.03	3.58 ± 0.09	0.07 ± 0.007
Janat	0.28 ± 0.03	3.49 ± 0.08	0.08 ± 0.009
Akan	0.2 ± 0.02	1 ± 0.04	0.001 ± 0.001
Adilette	0.18 ± 0.02	0.9 ± 0.05	0.001 ± 0.001
Maxat	0.19 ± 0.02	0.8 ± 0.04	0.001 ± 0.001

Note: *values are given as arithmetic means ± SD estimates calculated based on triplicate analysis of each pooled sample. SDs are estimated within the typical accuracy limits of the atomic emission spectrometry method (EXPEC 6500)*
Source: *compiled by the authors*

A comparison of the data obtained with the maximum permissible concentrations established by the International Atomic Energy Agency (2014) showed that the normative values were exceeded in most of the samples studied. According to these standards, the permissible levels of radionuclides in the aquatic environment are as follows: Cs-137 2 Bq/l, Am-241 0.2 Bq/l, Pu-239/240 0.005 Bq/l. The analysis revealed that the concentration of Cs-137 in water bodies reached 5.22 Bq/l, which is 2.6 times higher than the established limit. Am-241 also exceeded the permissible levels, reaching 0.5 Bq/l, especially in the areas of emergency and maximum radiation risk. Pu-239/240 was recorded in the range of 0.07-0.1 Bq/l, which is significantly higher than the limit value set by the International Atomic Energy Agency.

The largest exceedance of permissible concentrations of radionuclides in the water environment was recorded in the settlements of Yer Zhanybek, Baishuak, Akbulak and Abyraly, where the content of Cs-137 and Am-241 significantly exceeded the background level. These settlements are located near the epicentres of ground and atmospheric nuclear tests, which led to the formation of foci of migration of radionuclides from soil to water. Accounting for the registered concentrations, it is necessary to strengthen control of water resources and organise systematic radiation monitoring to assess environmental and sanitary risks. Of particular concern is the high mobility of Cs-137, which is manifested in its ability to desorb and spread with surface and groundwater runoff. This is confirmed by its maximum concentrations in areas of extreme radiation risk. While Pu-239/240 remains predominantly fixed in the soil profile due to its low solubility and high sorption capacity, its presence in water samples indicates the possibility of local mobilisation (Hussain *et al.*, 2022). Despite the absence of critical levels of contamination, the recorded exceedances of thresholds for Cs-137, Am-241 and Pu-239/240 require consideration in the environmental zoning of the territory, planning of agricultural use and water supply. Continuous radiation and hygiene monitoring are necessary to prevent the chronicity of radiation's impact on ecosystems and the population.

Accumulation of radionuclides in vegetation and feed. Vegetation cover participates in the redistribution of radionuclides in the ecosystem and their transfer through food chains. In the area of the Semipalatinsk nuclear test site, the main flora species are fescue-wormwood and forb communities, in particular *Stipa lessingiana*, *Festuca valesiasa*, *Artemisia sublessingiana*, and *A. albida*. Plants growing in conditions of radioactive contamination are capable of accumulating radionuclides, which poses a potential hazard to farm animals and humans (Filss *et al.*, 1998). The process of radionuclide accumulation is determined by several factors, including the chemical form of the element, soil acidity and particle size distribution, depth of the root system, growing season and plant species. Cs-137 proved to be the most mobile of the studied radionuclides, as it is actively absorbed by plant roots, translocated to aboveground organs and can be involved in cellular metabolic processes. At the same time, Pu-239/240 is characterised by low solubility and strong sorption on soil particles, which limits its bioavailability. Am-241 demonstrates an intermediate degree of mobility and accumulation in biomass.

The analysis of plant samples taken in areas with different levels of radiation risk showed pronounced spatial differences in radionuclide content. In the extreme radiation risk zone, covering the settlements of Yer Zhanybek, Kulzhan ata and Baishuak, maximum concentrations of Am-241 were recorded at 1.55-1.6 Bq/kg, Cs-137 1.97-2.2 Bq/kg, Pu-239/240 0.8-0.9 Bq/kg. These values significantly exceed the natural background levels accepted in international practice: for Cs-137 no more than 0.1 Bq/kg, for Am-241 1 Bq/kg, for Pu-239/240 0.1-0.3 Bq/kg. In the zone of maximum radiation risk, including Kainar, Abyraly and Akbulak, the concentrations of the studied radionuclides were lower, but still exceeded the permissible levels established for plant samples: for Cs-137 (1.6-1.9 Bq/kg) 16-20 times higher than the background (0.1 Bq/kg), Pu-239/240 (0.6-0.7 Bq/kg) 2-6 times higher than the upper limit of the norm (0.3 Bq/kg), while Am-241 (0.85-1 Bq/kg) was close to the indicative threshold of 1 Bq/kg. Plants predominant in these areas were cereals and sagebrush species, which could contribute to the intensive accumulation of radionuclides from the upper soil horizons (Table 3). The values of radionuclide concentrations in plant samples were calculated using formula (1).

Table 3. *Radionuclide content in crop samples (Bq/kg)*

Settlement	Am-241	Cs-137	Pu-239/240
Er Zhanybek	1.6±0.3	2.2±0.1	0.9±0.1
Kulzhan ata	1.55±0.1	1.97±0.3	0.8±0.2
Baishuak	1.56±0.3	2±0.2	0.9±0.1
Kainar	1±0.3	1.9±0.3	0.7±0.2
Abyrals	0.85±0.3	1.6±0.1	0.6±0.2
Akbulak	0.9±0.3	1.8±0.2	0.7±0.2
Rustem	0.5±0.2	0.8±0.2	0.4±0.1
Bayan	0.5±0.2	0.75±0.2	0.2±0.1
Janat	0.4±0.1	0.8±0.2	0.4±0.1
Akan	0.3±0.1	0.3±0.1	0.09±0.03
Adilette	0.2±0.1	0.2±0.1	0.08±0.03
Maxat	0.3±0.1	0.3±0.1	0.09±0.03

Note: *values are given as arithmetic means ± SD estimates calculated based on triplicate analysis of each pooled sample. SDs are estimated within the typical accuracy limits of the atomic emission spectrometry method (EXPEC 6500)*
Source: *compiled by the authors*

Comparison with the data on soil and water confirms the close relationship between the level of radioactive contamination of the environment and the content of radionuclides in plants. In the areas where Cs-137 concentrations in soil reached 1.83 Bq/kg and in water 5.22 Bq/l, the highest content of Cs-137 in plant biomass was observed. This confirms the active migration of the radionuclide through ecosystem components. In contrast, Pu-239/240, despite its soil stability, accumulated in plants in much smaller amounts due to its chemical and physicochemical properties. The concentrations of Am-241 in vegetation correlated with its levels in soil, but varied within a wider range, which may indicate differences in the ability of plants to absorb it. Given that the region's agriculture is based on pasture-based livestock farming, the detected concentrations of radionuclides in feed pose a potential threat. One cow consuming vegetation from an area of up to 160 m^2 daily can accumulate significant doses of Cs-137, which is then transmitted with milk and meat (Levchuk *et al.*, 2025). This is especially true in areas with the highest levels of contamination. The accumulation of Pu-239/240 in animals is slower, but its radiotoxicity is much higher, which increases sanitary and hygienic risks.

The results obtained indicate persistent contamination of the ecosystem with long-lived radionuclides that continue to circulate in biogeochemical cycles decades after the cessation of nuclear testing. Despite the relative decrease in concentrations in several settlements, the presence of Cs-137, Am-241 and Pu-239/240 in the fodder base requires constant monitoring, especially in the context of seasonal migration of radionuclides and possible climate change. Monitoring the content of radionuclides in vegetation should be a priority task when developing strategies for sustainable agricultural development in the Semipalatinsk landfill area.

Mechanisms of accumulation and redistribution of radionuclides in the region's ecosystems. The study of radioactive contamination in the Semipalatinsk nuclear test site area has revealed the key mechanisms of accumulation and redistribution of long-lived radionuclides (Am-241, Cs-137 and Pu-239/240) in various natural environments. The migration processes of these elements are determined by the geochemical conditions of the region, soil type, hydrological characteristics and biological features of the local flora and fauna. The analysis of soil samples showed that the main factors affecting the content of radionuclides are the level of radioactive exposure, properties of the soil horizon, depth of occurrence, as well as local landscape features affecting the migration of radionuclides. Cs-137 was characterised by high adsorption by clay minerals and organic compounds, which resulted in its more uniform distribution in the soil profile. At the same time, Pu-239/240, which has extremely low solubility, was predominantly fixed in the upper horizon. This is confirmed by both the high content of the isotope in the soil (up to 0.012 Bq/kg) and its minimum concentration in water (up to 0.001 Bq/l). Am-241 was found in smaller quantities but showed local accumulation, probably related to leaching processes and the physical and chemical composition of the soil. The vertical distribution of radionuclides confirms their limited migration: Cs-137 and Am-241 were concentrated at a depth of 0-10 cm, while Pu-239/240 was detected at 15-20 cm.

The content of radionuclides in water samples also varied depending on the radiation risk category. The maximum values of Cs-137 in water reached 5.22 Bq/l (Er Zhanybek), which exceeds the maximum permissible level set by the International Atomic Energy Agency (2014) (2 Bq/l) by more than 2.6 times. Am-241 concentrations in some locations were 0.5 Bq/l, which is also 2.5 times higher than the permissible level (0.2 Bq/l). The situation is similar with Pu-239/240, where the recorded values (0.1 Bq/l) exceed the recommended limit (0.005 Bq/l) by a factor of 20. The permissible levels of Cs-137, Am-241 and Pu-239/240 in water are 11, 0.69 and 0.55 Bq/l, respectively, and exceedances were recorded only for Cs-137 in the emergency risk zone, but the data remain below the national limit.

Plants sampled from the studied pastures showed that the levels of Am-241 (up to 1.6 Bq/kg) and Cs-137 (up to 2.2 Bq/kg) exceeded the estimated background levels of uncontaminated areas (0.1-0.3 Bq/kg according to the International Atomic Energy Agency) by 7-20 times. This indicates the bioavailability of radiocaesium and americium and their active assimilation by grass vegetation. The concentrations of Pu-239/240 in plants (up to 0.9 Bq/kg) also significantly exceed the natural level (usually <0.01 Bq/kg), indicating its participation in the biological cycle under conditions of intensive contamination. A comparison of the radionuclide content in the three media showed that in the emergency risk zone, Cs-137 levels in the soil are on average 1.5 times higher than in plants and 3.5 times higher than in water, while Pu-239/240 demonstrates maximum retention in soil and minimum retention in water.

Fodder grown on pastures in contaminated areas represents a potential pathway for radionuclides to enter the body of animals and, consequently, livestock products (Lazarev & Klepko, 2023). Studies show that cattle consume vegetation mass from an area of up to 160 m^2 per day, which increases the likelihood of radionuclide accumulation in animal tissues. The greatest danger is posed by Cs-137, which is actively involved in metabolic processes and can accumulate in muscle tissue and milk. Pu-239/240 and Am-241, having low bioavailability, accumulate in bone tissue and internal organs, which requires special control over the safety of meat and offal. The accumulation of radionuclides in feed confirms the need for systematic monitoring of agricultural land and the development of measures to reduce the radiation load (Shaforost *et al.*, 2024).

The concentrations of radionuclides in the soil in the extreme risk zone (Er Zhanybek, Kulzhan ata, Baishuak) are as follows: Am-241 up to 0.55 Bq/kg, Cs-137 up to 1.83 Bq/kg, Pu-239/240 up to 0.012 Bq/kg. These values also exceed the indicative maximum permissible levels (0.3 Bq/kg for Am-241, 0.6 Bq/kg for Cs-137 and 0.02 Bq/kg for Pu-239/240) by 1.8-3 times for Cs-137 and Am-241. Consequently, soil remains the main depot of radionuclide contamination, with the level of accumulation exceeding similar values in water and vegetation by an average of 3-5 times. Periodic radiation monitoring of soil and vegetation is recommended, especially on agricultural land. The use of potassium fertilisers can reduce the uptake of Cs-137 by plants, and the reclamation of pastureland will minimise the risk of radionuclides entering livestock products. In addition, it is necessary to develop a strategy for remediation of contaminated areas to reduce their radiation hazard. Thus, the study confirmed that the mechanisms of accumulation and redistribution of radionuclides in the region's ecosystems are determined by several natural and anthropogenic factors. Continued monitoring studies and the implementation of appropriate protective measures will minimise environmental and radiation risks in the former Semipalatinsk nuclear test site.

DISCUSSION

The results of the study showed that the content of Am-241, Cs-137 and Pu-239/240 in soil, water and vegetation varies depending on the level of radiation risk in the studied areas. The identified differences in radionuclide concentrations indicate complex processes of migration and accumulation caused by natural and anthropogenic factors. Comparative analysis will help to clarify the patterns of radionuclide migration and provide a more accurate assessment of long-term environmental impacts.

A comparison of the data obtained with the results of other authors confirmed the complexity and multiethiological nature of radioecological processes in the region. The results of the present study, in which Cs-137 and Am-241 concentrations above background values were recorded in soil and water samples in the settlements of Akan, Adilet and Maksat, are consistent with the findings of A. Lipikhina *et al.* (2025), found that radioactive contamination of the southeast of the Abay region may be caused not only by the impact of the Semipalatinsk nuclear test site but also by transboundary transfer of radionuclides from the Chinese Lob Nor test site. The obtained values of Pu-239/240 accumulation in soil (up to 0.012 Bq/kg) and in plants (up to 0.9 Bq/kg) correspond to the observations of S. Arynova *et al.* (2024), who found a significant accumulation of actinides, including uranium and thorium, in natural components of the surrounding areas, indicating a complex composition of the radiation background.

S. Duyssembaev *et al.* (2018) emphasised the high mosaic nature of the radionuclide distribution, and the data of the present study confirmed this conclusion: the spatial distribution of alpha and beta radiation varied widely even within the same risk zone. In addition, K. Hanaček and J. Martinez-Alier (2024) noted that the unevenness of contamination in post-Soviet countries is exacerbated by the lack of availability of environmental remediation. The Cs-137 concentrations exceeding the maximum permissible concentration in water bodies (up to 5.22 Bq/l) recorded in Yer Zhanybek and Baishuak demonstrate the relevance of these findings and the need to expand monitoring and radiation safety measures in remote areas. The results of the water sample analysis, in which Pu-239/240 concentrations did not exceed 0.001 Bq/l, confirmed the extremely low solubility of this radionuclide and its low mobility, which limits its participation in water migration. At the same time, the recorded concentration of Cs-137 in the range of 0.8-5.22 Bq/l significantly exceeded the regulatory values of the International Atomic Energy Agency (2 Bq/l), especially in Yer Zhanibek, Bayshuak and Akbulak, indicating its high migratory capacity. These data are consistent with the results of D.K. Gupta and C. Walther (2025), where Cs-137 is characterised as the most mobile radionuclide, actively circulating in ecosystems and capable of desorption and transfer to the water phase. The values identified are also consistent with the observations of D. Dasher *et al.* (2002), highlighting cases of radionuclide leakage from underground nuclear test sites into surface waters, which is similar to the possible scenario for the Semipalatinsk test site.

The results obtained for radionuclide accumulation in vegetation, which recorded maximum concentrations of Am-241 (1.55-1.6 Bq/kg), Cs-137 (1.97-2.2 Bq/kg) and Pu-239/240 (0.8-0.9 Bq/kg) in areas with high levels of soil contamination (Er Zhanibek, Kulzhan Ata, Bayshuak) confirmed the close relationship between radionuclide content in soil and their uptake into plant biomass. These data were consistent with the conclusions of M. Gerzabek *et al.* (2024), which emphasised that the physical and chemical characteristics of the soil determine the sorption capacity and bioavailability of radionuclides to plants. The results of feed sample analysis, which showed exceedances of natural background levels, also confirmed the potential risks to livestock farming, which is consistent with the data of T. Ponomaryova *et al.* (2022), which found accumulation of Cs-137 and Sr-90 in crops grown on contaminated soils. In addition, a study by A. Yankauskas *et al.* (2024) recorded morphological and anatomical changes in plants exposed to radioactive contamination, which may explain the physiological response of vegetation to radionuclide accumulation, similar to that observed in the present study. N. Akhtaeva *et al.* (2022) demonstrated the adaptive mechanisms of plants under conditions of technogenic pollution, which is consistent with the facts of active absorption of Cs-137 and Pu-239/240 by forage plant samples, especially in areas of maximum radiation risk.

The revealed results emphasised the need for further study of the processes of radionuclide transfer to plant biomass and their subsequent inclusion in food chains. The recorded concentrations of Cs-137, Am-241, and Pu-239/240 in plant samples from areas of varying degrees of contamination confirmed the high dependence of radionuclide accumulation on the level of soil contamination. These observations coincided with the results of J. Guillén *et al.* (2022), who proposed using stable isotopes of Cs and Sr as indicators of the migration of radioactive analogues in the soil-plant system for monitoring in contaminated areas. The concentrations of radionuclides in plant biomass recorded in the studied areas in some cases exceeded the background level, which is consistent with the findings of S. Endo *et al.* (2008), where it was shown that vegetation in the vicinity of nuclear test zones can actively accumulate radionuclides in amounts that can have a long-term impact on ecosystems. Differences in the levels of radionuclide accumulation in the studied samples were explained by both textural and chemical characteristics of the soil and peculiarities of the morphology and physiology of the plants themselves.

The results of spectrometric analysis of soil samples showed that radionuclide levels in most of the studied areas did not exceed the maximum permissible values, but in the extreme radiation risk zone (Yer Zhanybek, Kulzhan ata, Baishuak) local zones with increased content of Cs-137 (up to 1.83 Bq/kg at a norm of 0.6 Bq/kg) and Am-241 (up to 0.55 Bq/kg at a norm of 0.3 Bq/kg), indicating residual contamination of the upper soil horizon. These observations confirmed the position of B. Penati (2019), according to which the scale of radioactive contamination on the territory of the former Semipalatinsk test site may be significantly underestimated. The data obtained showed the persistence of radionuclides in the soil decades after the completion of nuclear tests. In contrast to soil, in water samples, Pu-239/240 concentrations in several settlements significantly exceeded the maximum permissible value set by the International Atomic Energy Agency (0.005 Bq/l), reaching 0.1 Bq/l, which is 18-20 times the permissible level. This contradicts the results of X. Zhao *et al.* (2020), who recorded low plutonium mobility in natural waters. The reason for the discrepancies may be the specific geohydrological conditions of the studied areas or local leaching zones in the upper soil horizons containing residual amounts of Pu-239/240.

The highest levels of radiation contamination were recorded near the epicentres of nuclear explosions, where increased concentrations were observed in both soil and vegetation. Similar patterns were described by S. Duyssembaev *et al.* (2014), who, based on a comprehensive analysis of the components of the soil-plant-animal system, showed that even decades after the tests were completed, radioactive contamination pockets remain in the region, which can affect biogeochemical cycles. The data obtained confirmed the presence of such zones, especially in areas of extreme and maximum radiation risk, which requires continued monitoring and corrective measures.

The analysis of the spatial distribution of Pu-239/240 in soil and water showed significant differences in its behaviour in different natural environments. In soil samples, Pu-239/240 concentrations in most of the studied areas remained within the permissible limits, indicating its limited mobility and high sorption capacity. However, in water samples collected in areas of extreme radiation risk, Pu-239/240 concentrations reached 0.1 Bq/l. These data are consistent with the observations of C. Re (2024), who noted the transformation of soil and plant ecosystems under conditions of post-nuclear impact and the long-term persistence of residual radionuclides. The recorded low mobility of Pu-239/240 in soil and its minimal presence in the aquatic environment confirm the conclusions of E. Harrell and D. Hoffman (2013), according to which a significant portion of plutonium at the site is retained in isolated forms that are not involved in migration processes. The results obtained suggest that Pu-239/240 may participate in migration processes under certain hydrogeochemical conditions at the Semipalatinsk landfill.

The analysis of the data obtained revealed that in the areas with the maximum content of radionuclides, especially Cs-137 in water and Am-241 in plants, a high level of radioecological risk remains, which requires an assessment of the possibilities for local environmental remediation. The results showed that in the Yer Zhanybek zone, Cs-137 concentrations in water reached 5.22 Bq/l, while the norm is 2 Bq/l, and Am-241 content in plant biomass was 1.6 Bq/kg, while the permissible level is 1 Bq/kg. These indicators indicated a potential threat of biological transfer of radionuclides and the need for targeted remediation of contaminated areas. Such conclusions are consistent with the position of C. Evans (2022), who emphasises the limitations of current international efforts to address the consequences of nuclear testing. P. Högselius and A. Klüppelberg (2024) emphasised that the consequences of the Soviet nuclear legacy remain unresolved in several post-Soviet regions, which is consistent with the local areas of exceedance of permissible levels of radionuclides recorded in the present study. The presence in some areas of concentrations many times higher than the standards requires expanded monitoring and the development of localised strategies to reduce the radiation burden. The results confirm the presence of localised radioactive contamination on the territory of the former Semipalatinsk nuclear test site, with differential distribution of radionuclides in soil, water and vegetation. Comparison with other studies shows similarities in Cs-137 migration processes and Pu-239/240 persistence, which requires further monitoring to assess the long-term impact on the ecosystem and potential risks to public health.

CONCLUSIONS

A study of the radioecological situation in the former Semipalatinsk nuclear test site revealed varying degrees of contamination of soil, water, vegetation and fodder with long-lived radionuclides Am-241, Cs-137 and Pu-239/240. The data analysis confirmed the complexity of the spatial distribution of radionuclides due to the peculiarities of the soil profile, hydrogeochemical processes, biological migration and natural factors. The study of soil samples showed that the maximum levels of specific activity of radionuclides were recorded in the Yer Zhanybek zone, where the concentrations of Cs-137 were 1.83 ± 0.15 Bq/kg, Am-241 0.55 ± 0.03 Bq/kg, and Pu-239/240 0.012 ± 0.0015 Bq/kg. In most other locations studied, the concentrations did not exceed the maximum permissible values, but local areas with exceeding values were identified, which required additional studies. The distribution of Pu-239/240 was limited to the upper soil horizons (0-15 cm), which confirmed its low migration capacity. Cs-137 and Am-241 were localised mainly in the 0-10 cm layer, showing limited vertical movement.

The results of the water sample analysis confirmed the presence of radionuclides in surface and groundwater sources, indicating possible migration pathways. The highest concentrations of Cs-137 were recorded in the Yer Zhanybek area (5.22 ± 0.2 Bq/l), which was more than twice the permissible level according to the International Atomic Energy Agency (2 Bq/l). Am-241 concentrations in water ranged from 0.18 to 0.5 ± 0.4 Bq/l, which also exceeded the standard of 0.2 Bq/l. The concentrations of Pu-239/240 in the water environment at several points (up to 0.1 ± 0.3 Bq/l) exceeded the threshold of 0.005 Bq/l by a factor of 20, which indicated possible instability of its fixation in the soil. The vegetation cover confirmed its role in the biological migration of radionuclides. In the areas of maximum and extreme radiation risk, concentrations significantly exceeding the permissible levels were recorded: the content of Cs-137 in plants reached 2 ± 0.1 Bq/kg, which is 16-20 times higher than the background level (0.1 Bq/kg), Pu-239/240 up to 0.9 ± 0.1 Bq/kg, which is 3-9 times higher than the upper limit of the norm (0.3 Bq/kg). Am-241 concentrations ranged from 0.85 to 1.6 Bq/kg, approaching or exceeding the guideline value of 1 Bq/kg recommended for plant samples. These results indicate the active participation of herbaceous vegetation in the accumulation of radionuclides and confirm the risks of their entry into food chains.

The results of the study show that the radiation situation in the studied areas remains stable but requires regular monitoring. Radioactive elements, especially Cs-137, continue to persist in the environment, which poses a potential threat to ecosystems and the population. In the future, it is recommended to introduce additional measures to reduce the radioactive load, including phytoremediation, the use of sorbents to bind radionuclides in the soil, and restriction of agricultural use of pastures in areas of increased radiation risk. A comparative analysis of soil, water and vegetation samples showed that the level of radioactive contamination of water with Cs-137 and Am-241 exceeded that of soil by a factor of 3-10. This indicated the redistribution of radionuclides from the soil horizon to the water environment. Despite the overall low mobility of Pu-239/240, its concentrations in some water samples exceeded the permissible values by 15-20 times, indicating local migration processes. Cs-137 showed the highest mobility in natural environments, actively transferring from soil to water and vegetation. On the contrary, Pu-239/240 was retained mainly in soil, which limited its participation in biogeochemical cycles, but did not exclude occasional release to other environmental components. It is advisable to conduct further studies considering seasonal fluctuations in contamination and expanding the network of control points to improve the accuracy of radioecological assessment. It is important to study in more detail the processes of biological remediation and the impact of radionuclides on agricultural ecosystems.

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Радіоекологічний стан довкілля в зоні колишнього Семипалатинського ядерного полігону

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Анотація. Радіоактивне забруднення довкілля в районі колишнього Семипалатинського ядерного полігону (Казахстан) зумовлене осадженням і тривалим збереженням у ґрунті, воді та рослинності довгоживучих радіонуклідів, що створює потенційні ризики для екосистем і здоров'я населення. Мета дослідження полягала в оцінці рівнів забруднення ґрунту, води та рослинності радіонуклідами америцій-241, цезій-137 і плутоній-239/240 на територіях різного радіаційного ризику в районі колишнього Семипалатинського ядерного полігону. Радіаційно-екологічний моніторинг проведено на дванадцяти контрольних пунктах з використанням спектрометричного аналізу для визначення питомої активності зазначених радіонуклідів у пробах навколишнього середовища. У результаті дослідження було встановлено виражені відмінності у вмісті радіонуклідів у ґрунті, воді та рослинності на територіях із різним рівнем радіаційного ризику. Максимальні концентрації америцію-241 (0,55 ± 0,03Х Бк/кг), цезію-137 (1,83 ± 0,15 Бк/кг) і плутонію-239/240 (0,012 ± 0,0015 Бк/кг) зареєстровано в зоні надзвичайного радіаційного ризику, тоді як у найменш забруднених районах їхні рівні були нижчими в 4-7 разів. У водних об'єктах найбільшу активність відмічено у цезію-137, концентрація якого сягала 5,22 ± 0,2 Бк/л, що істотно перевищує допустимі нормативи. У рослинності виявлено значне накопичення всіх трьох радіонуклідів: Am-241 – до 1,6 ± 0,3 Бк/кг, Cs-137 – до 2,2v± 0,1 Бк/кг, Pu-239/240 – до 0,9 ± 0,1 Бк/кг. Найбільші рівні зафіксовано в зонах надзвичайного та максимального ризику, переважно в пасовищних злакових культурах. Проведений аналіз вертикального розподілу радіонуклідів засвідчив їх диференціацію за глибиною: Cs-137 та Am-241 зосереджені у верхньому шарі ґрунту (0-10 см), тоді як Pu-239/240 частково мігрував до 15-20 см, що підтверджувало ризик їхнього включення до трофічних ланцюгів та необхідність подальшого моніторингу. Отримані дані можуть бути використані при плануванні заходів з екологічної реабілітації забруднених територій, регулюванні сільськогосподарського використання пасовищ і забезпеченні радіаційної безпеки населення

Ключові слова: радіаційне забруднення; америцій-241; цезій-137; плутоній-239/240; ґрунт; вода; рослинність