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Radiological Assessment of the Min-Kush Uranium Tailing Dump and the Specifics of Its Rehabilitation

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ABSTRACT

This study examines the current radioecological condition of the former uranium production site in the village of Min-Kush, Kyrgyzstan, which was one of the largest uranium mining centers in the Soviet Union. From 1946 to 1970, Kyrgyzstan served as the primary uranium-producing republic of the USSR, leaving behind a vast legacy of radioactive waste. Inefficient mining and ore processing during this period resulted in the accumulation of approximately 7.5×10^8 m^3 of radioactive residues stored in tailings and spoil heaps distributed across the country. One of the key facilities associated with this legacy is the Kara-Balta Mining Plant (KGRK), which remains the largest uranium-processing enterprise in Central Asia. This article presents the findings of a comprehensive radioecological assessment conducted in Min-Kush, including former production sites, mining shafts, industrial infrastructure, and adjacent territories. The study was carried out in accordance with the recommendations of the International Atomic Energy Agency (IAEA) using the ERICA Tool 2 software for environmental risk assessment. The methodology included field sampling, radiometric measurements, site mapping, and data analysis to evaluate residual contamination levels and their ecological impact. The results show that all major contaminated sites, including industrial buildings and surrounding lands, have been remediated in accordance with international environmental and radiation safety standards. Post-rehabilitation monitoring confirms that radiation levels have been reduced to natural background values. This case study of Min-Kush provides an important example of

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successful reclamation of former uranium production areas and serves as a reference for future environmental restoration projects in post-Soviet regions.

Keywords: Radionuclides; Uranium; Waste Dump; Tailings Storage Facilities; Soil; Water; Bottom Sediments; Rocks

1. Introduction

Kyrgyzstan is one of the most vulnerable countries to climate change in Central Asia and climate change has a direct impact on the distribution of natural resources. Mining enterprises located among extremely vulnerable high-mountain ecosystems pose a particular danger. More than 90 percent of Kyrgyzstan lies above the 1,000 m contour, so the republic is essentially a high-mountain country. This rugged topography makes local ecosystems acutely vulnerable to any kind of disturbance — natural, technogenic, or purely anthropogenic. The mosaic of climates that spans the Tien Shan and Pamir-Alai ranges, from hot semi-desert steppe belts to cool alpine and sub-alpine zones, has generated highly diverse environmental niches [1–4]. In such geologically young mountain systems, like the Tien Shan and Pamir-Alai, the usual regularities that govern soil development and radio- or biogeochemical cycling are often weakly expressed or entirely absent. Therefore, the violation of the ecological balance in the mountains leads to unpredictable consequences in adjacent territories.

The presence of waste stored in dumps and tailings in the republic, due to inefficient extraction and irrational processing of minerals (1946–1970), led to environmental problems such as subsoil depletion, soil pollution, with a high content of a number of potentially dangerous radionuclides and chemical elements and their compounds **(Figure 1)** [5–7].

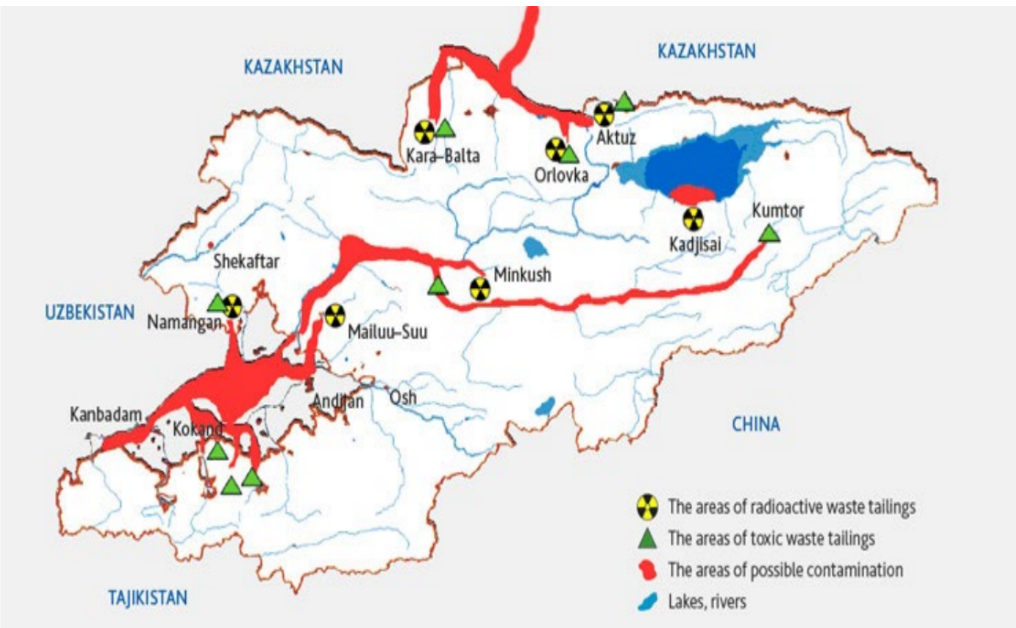

Figure 1. Radioactive and Toxic Waste on the Territory of Kyrgyzstan.

The Kara-Balta Mining Plant processed radioactive raw materials for the defense and energy needs of the Soviet Union for about 40 years (1955–1991), producing over 60 thousand tons of uranium and 15 thousand tons of molybdenum during these years. The decision to build the Kara-Balta Mining Plant in the territory of the Kyrgyz Republic was made on October 24, 1950, by Resolution of the Council of Ministers of the USSR No. 4381-1854. During the existence of the USSR, the upper southern part of the city of Kara-Balta was a closed "mailbox" with several classified industries, including the main enterprise of the city — the Kara-Balta Mining Plant (KBMP) [6].

Since the mid-1950s Kyrgyzstan has taken eighteen mines out of operation—four of them former uranium producers. The country now has 33 tailings impoundments and 21 waste-rock dumps. A large share of these facilities lies inside the catchments of international rivers such as the Naryn, Mailuu-Suu, Sumsar and Chu, posing cross-border hazards to Kyrgyzstan, Kazakhstan, Tajikistan and Uzbekistan and potentially affecting more than five million people. Several impoundments stand just outside settlement boundaries—including Mailuu-Suu, Min-Kush, Shekaftar, Sumsar, Kadji-Sai, Ak-Tyuz and Kan—heightening local risk [6].

To mitigate this legacy, the government has approved a site-specific programme that prescribes safety, reclamation and rehabilitation measures for every tailings pond and waste dump. Within the Regional Environmental Action Plan (REAP) adopted by the Interstate Commission on Sustainable Development and backed by UNEP, Kyrgyzstan coordinates the priority track on "waste management."

In order to ensure radiation safety of the population of the Kyrgyz Republic, the following normative legal acts have been adopted: "On radiation safety of the population of the Kyrgyz Republic", "On tailings and mine dumps", "On environmental protection", "Technical regulations "On radiation safety" and "General technical regulations for ensuring environmental safety in the Kyrgyz Republic", by the Resolution of the Government of the Kyrgyz Republic dated August 5, 2015 No. 558, guidelines in the field of handling radioactive substances and sources of ionizing radiation were approved, as well as a number of by-laws: decrees, regulations, instructions, SNiPs, etc.

In the Kyrgyz Republic, taking into account all types of emergency situations, including man-made and environmental emergencies [8,9], the relevant authorized state bodies are engaged, among which a special place is occupied by *the Agency for Tailings of the Ministry of Emergency Situations of the Kyrgyz Republic (2012) and the Agency has a group of highly qualified rapid response specialists with the appropriate equipment and inventory. A state program for radiation monitoring has been created, where periodic monitoring of the state of uranium tailings and dumps is carried out with the involvement of scientific specialists from the National Academy of Sciences of the Kyrgyz Republic.*

The role of the Institute of Biology of the National Academy of Sciences of the Kyrgyz Republic in this process, as a scientific and expert body in the republic, is relevant. The institute conducts research in several priority areas of scientific and practical research and development, including:

- Rational use of natural resources;
- Comprehensive studies of natural and natural-technogenic processes in mountainous areas;
- "Ecological, biogeochemical and radiological monitoring of the natural and man-made environment":
- Comprehensive ecological and biogeochemical assessment of the current state of mountain ecosystems (uranium and other natural and man-made provinces [10].

To solve the problems, research is carried out by researchers of the Institute of Biology of the National Academy of Sciences of the Kyrgyz Republic together with leading foreign scientists and specialists in this field. In connection with the solution of a number of environmental problems, radioecology, biogeochemistry and geochemical ecology are acquiring new significance in the republic, the relevance of problems associated with radioecology, radiobiogeochemical and biogeochemical zoning, mapping and standardization is increasing. At present, biogeochemistry and radiobiogeochemistry are becoming the basis and source of vitally important applied and theoretical areas of science, and biogeochemical and radiobiogeochemical methods of mineral exploration, sections of chemical systematics of plants and geobotany, general ecology and radioecology, biotechnology, medical geography and hygiene, environmental protection, veterinary science and plant growing are becoming a tool for the development of areas [11–15].

Serious geological, environmental threats and problems of global climate change have a constant negative impact on the population and economy of the republic. In this regard, it is necessary to note the rehabilitation work carried out in man-made territories by national companies and institutions.

Currently, a special place is occupied by the activities of the Limited Liability Company "ERN-Stroy" (OSOO "ERN-Stroy"), which carries out reclamation and rehabilitation of former uranium territories in the mountainous regions of Kyrgyzstan. During the rehabilitation of tailings, OSOO "ERN-Stroy" uses advanced technologies, an innovative approach that allows for not polluting the clean zone and not spreading contaminated tailing materials.

Taking into account the importance and significance of radioecological and ecological-biogeochemical studies in Kyrgyzstan and the region in the area of former uranium mining operations, the goal is to assess the current state and systematize the results of earlier ecological-biogeochemical and radioecological studies of the Min-Kush uranium-natural-technogenic province before and after rehabilitation.

2. Materials and Methods

Field work spanned the Min-Kush technogenic–natural province both before and after remediation activities. Site coordinates were captured at regular intervals with a GPS handheld, providing exact latitude-longitude fixes for every measurement. Ambient gamma radiation was charted using a DKS-96 dosimeter-radiometer from the Institute of Biology's Biogeochemistry and Radioecology Laboratory (National Academy of Sciences of the Kyrgyz Republic). Field work at all sites included measuring geographic coordinates, measuring the values of the exposure dose rate (DER), sampling (OS), and labeling the sample was carried out according to generally accepted methods. Measurements were carried out in accordance with the IAEA instructions for ground-based survey of the radiation situation at an altitude of 0.1 and 1 метрfrom the earth's surface. According to the technical instructions of the dosimeters, measurements at one point were taken at least three times, then the arithmetic mean was determined [16–22].

Soil research and soil sampling were carried out in accordance with GOST 17.4.3.01-83 "General requirements for soil sampling". General soil analysis was carried out at the Republican Soil-Agrochemical Station under the Ministry of Agriculture of the Kyrgyz Republic. Soil samples were taken from the upper horizons (up to 20–25 cm), where nutrients and chemical pollutants are mainly concentrated. Soil sampling was carried out at the following sites:

- Within and near the Tuyuk-Suu tailings dump;
- Within and near the Taldy-Bulak tailings storage facility;
- Territory of the village of Min-Kush, area of adits at sites No. 17 and 21;
- Within and near the tailings storage facility "Kak";
- Within and near the Dalniy tailings storage facility.

When collecting soil samples, each sample was placed in a plastic bag and labeled with the name of the sample, location and date (**Figure 2**) [7].

Figure 2. Soil Sampling and Preparation for Analysis.

The area of the old processing plant, industrial site, etc. was regularly monitored and radiation doses of the deposits were recorded. Complex scientific expeditionary studies were carried out periodically in 2015, 2017, during reclamation work and after rehabilitation in 2021 and 2023. Measurements of the activity of radionuclides in soils and grounds were carried out on a Canberra gamma spectrometer (USA), consisting of an HPGe germanium detector. The detector is made of special pure germanium from Canberra, model GX4019, control of the gamma spectrometric tract, processing of hardware gamma spectra with Genie-2000 software. All sample preparation, analytical work, and data processing from the expedition were completed in the Biogeochemistry and Radioecology Laboratory of the Institute of Biochemistry, National Academy of Sciences of the Kyrgyz Republic. *The object of radioecological and biogeochemical studies was the current state of the for-*

mer Min-Kush uranium production — production sites, mines, tailings storage facilities and adjacent areas (**Figure 3**)[10].

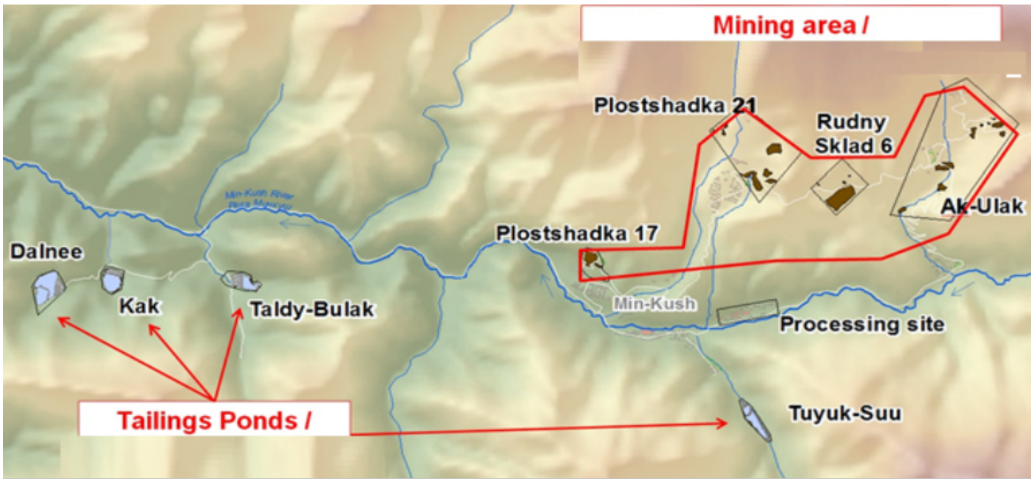

Figure 3. Map-Scheme of the Natural and Man-Made Province of Min-Kush.

3. Results

This study addresses an intricate, long-standing challenge that sits at the intersection of radioecology and biogeochemistry. These intertwined fields investigate how the elemental composition of living organisms influences the movement, conversion, and buildup of chemical species across the biosphere—a research trajectory originally charted in the early 1930s by Academician V. I. Vernadsky and his colleagues. In the present day, radioecological and biogeochemical inquiries have become frontline scientific priorities, shedding light on humanity's technogenic impacts and guiding efforts to balance human activity with natural processes.

Geographically, the territory of the former uranium mine "Min-Kush" is located in the spurs of the Moldo-Too ridge at an altitude of about 2000–2500 m above sea level, which closes the Dzhumgal valley from the south of the republic in the latitudinal direction. The Moldo-Too ridge and its numerous spurs, of various exposures, are part of the Tien Shan mountain system. The territory of the site belongs to the Min-Kush River basin, five kilometers upstream from the confluence of the Min-Kush and Kokomeren rivers. The main waterway of this territory is the Min-Kush River, which forms a large drainage basin. The rivers are fed by snow and glaciers and by the discharge of groundwater[2,4,7].

In total, there are four tailings ponds and four ore and mining dumps in the mountainous areas of the Min-Kush village of the Naryn region. According to modern estimates, those located near rivers are the most dangerous. All tailings ponds and mining dumps in the republic, with the exception of the tailings pond in the Kadji-Sai village, are located in the Naryn and Maily-Sai river basins and further into the Naryn, Syr Darya and Aral Sea rivers. For example, the Tuyuk-Suu dumps are located near the Min-Kush river in the Min-Kush village. The observed annual landslide near the river for several years poses a danger. If the landslide blocks the riverbed, the water can flood the tailings pond and carry the waste from it into the Naryn River. And the waste can reach the territory of the Aral Sea (**Figure 3**).

Consequently, before any reclamation began, the province was placed under a regular surveillance regime: systematic radioecological surveys examined soils, surface and ground waters, and representative plant communities, enabling us to chart radionuclide concentrations and trace their potential dispersion routes throughout the local environment.

Administratively, this territory belongs to the Jumgal district, Naryn region of the Kyrgyz Republic. The settlement of Min-Kush includes residential areas (microdistricts): No. 16, 17, 20, 21, Ak-Ulak, Dalniy Min-Kush, and Kyzyl-Sook. The difference in height of these areas can be up to several tens of meters, the maximum distance of the distant areas to the center is more than 10 км. In general, the areas are connected by a dirt road. The Min-Kush River flows through the village, into which the Tuyuk-Suu, Kara-Kungey and Dalniy Min-Kush rivers flow. It is known that the waters of the Min-Kush River flow into the Koko-Meren River, then into the Naryn and Syr Darya rivers[7].

In this province there are four tailing dumps (Tuyuk-

Suu, Taldy-Bulak, Kak and Dalnee) with radioactive materials with a volume of 1.15 thousand m^3, as well as four dumps with substandard ores. Recently, the most dangerous in this area is the Tuyuk-Suu tailing dump, located at the mouth of the Tuyuk-Suu River, where geomorphological processes occur (**Figures 4–7**)[7].

Figure 4. Landslides on the Right Bank of the Min-Kushriver and Below the Tuyuk-Suu Tailings Pond.

Figure 5. Drainage Channel from the Tuyuk-Suu Tailings.

Figure 6. Tuyuk-Suu Tailings Pond.

Figure 7. Water from Under the Tailings Storage Facility.

The tailings dumps in Min-Kush are flat areas of land located on slopes with a steepness of 20–40° between the mountains. The ore complex was operated from 1963 to 1969. After the closure of uranium production, all the tailings dumps were mothballed, but they did not meet the requirements of the international standard. In addition to these tailings dumps, on the territory of the settlement of Min-Kush there are adits, ore dumps and a former uranium ore enrichment plant. In some places, ore dumps were stored near watercourses and in open areas [7].

Previously conducted radiometric survey of the exposure dose rate of gamma radiation at various sites of the Min-Kush uranium tailings dumps showed from 27 to 60 μR/h, but in some places it was high, for example, at the Taldy-Bulak tailings dump 554–662 μR/h. The uranium content in the soil here, on average along the profile, fluctuates from 3.3 to 17.5 · 10^{-6} g/g, which is quite high. The territory located above the enrichment plant is particularly dangerous, where the uranium content in the soil reaches 30–35 · 10^{-6} g/g at the surface, which indicates local contamination of this zone. In general, the soils of the Min-Kush geochemical province are significantly enriched in uranium, since the uranium concentration in them is 5–6 times higher than the average readings in the soils of Kyrgyzstan [7,23,24].

Mountain dark chestnut and mountain meadow-steppe subalpine soil types are widespread in technogenic territories and near the former uranium mine “Min-Kush”. Vegetation, which is part of the Kokomeren-Minkushsky district, is dominated by spruce and juniper forests and sparse forests, meadows and steppes. Plant groups of rocky cliffs and screes are also widespread. There is floodplain vegetation and thickets of various shrubs, thorny cushion plants [7]. Other types of vegetation are poorly expressed [25–27].

Profile 1 — left bank of the Tuyuk-Suu. Topographic setting: north-east-facing slope, absolute elevation ≈ 2104 m. Location (GPS): 41° 39′ 34.2″ N, 74° 28′ 23.3″ E; instrument altitude 2014 m. Horizon 0–25 cm – dark-brown surface layer, still in the early stages of sod formation; herb-root network weak, pebble inclusions abundant. Horizon 25–50 cm – grey-brown, granular-lumpy structure; rootlets scarce. A distinct shift in colour and compaction marks the boundary with the overlying layer. Below 50 cm – pale brownish-grey matrix, slightly densified and moist; scattered carbonate flecks appear, transitioning downward into a zone dominated by coarse stones (see **Figure 8**).

Mountain meadow-steppe subalpine soils are formed under subalpine meadow-steppes on deluvium and eluvium of bedrock – granite, shale, limestone and sandstone. Climatic conditions in the formation zone of these soils are characterized by low average annual temperatures, a short growing season with an average annual precipitation of 400–500 mm [7,16,19].

These soils are confined to the mountain slopes of the village of Min-Kush. Plots No. 3, 4, 5, 6, 10. Morphologically, mountain meadow-steppe subalpine soils are characterized by:

- Gray-brown or brownish-dark gray color of the humus horizon;
- Lumpy-granular structure;
- Quite monotonous, loose structure of the entire profile;
- In mechanical composition, these soils are very diverse, from light to heavy loamy, often stony;

- Medium power.

To give an idea of the mountain meadow-steppe subalpine soil, we will give a description of the section laid on the surveyed area: Section 2. Mountainous area "Ak-Ulak". North-western exposure. Absolute height 2456 m. To give an idea of the mountain meadow-steppe subalpine soil, we will give a description of the section laid on the surveyed area: Mountainous area "Ak-Ulak"[7]. North-western exposure. Absolute height 2456 m.

GPS coordinates: h – 2456, N– 41˚41,203'E–074˚30, 201); A 0–25 *cm* Color: dark brown-gray, fresh, loose, lumpy, plant roots. B 25–50 cm gray, denser than the previous horizon, dry, lumpy-granular; C 50 cm and below cartilage, stones (**Figure 9**)[7].

Figure 8. View of Soil Section No. 1.

Figure 9. Soil Section View No. 5.

4. Discussion

The soil cover of the study object is represented by mountain dark chestnut and mountain subalpine-meadow-steppe soils. Mountain dark chestnut soils are also characterized as low to medium fertility, medium-stony, medium-deep, with various mechanical compositions. The humus content (**Table 1**) is as follows: in the 0–25 cm layer it fluctuates within 2.23–6.17%; total nitrogen 0.100–0.290%; phosphorus 0.080–0.145% and potassium 1.14–1.50%; the reaction of the soil solution is neutral to slightly alkaline – pH within 7.30–8.45[19,28].

Table 1. Soil-Agrochemical Analysis Indicators [7,10].

No.	Depth, cm	Humus, %	pH	Nitrogen General, %	Total Phosphorus, %	Gross Potassium [10], %
1	0–25	3.0	8.20	0,120	0,140	1.50
2	0–10	6.17	7.85	0.290	0.145	1.43
3	0–15	2.65	8.35	0,100	0,080	0.84
4	0–25	6.17	7.85	0.295	0.115	1.23
5	0–20	2.08	8,10	0.045	0,120	1.20
6	0–25	2.39	8.55	0.095	0,090	1.11
7	0–20	4.88	7.30	0,180	0.095	1.14
8	0–20	2.23	8.45	0,100	0,080	1.17
9	0–25	3.0	8.30	0.155	0.095	1.14
10	0–10	2.60	8.50	0,210	0,190	0.96 [7]

The mountain subalpine meadow-steppe soil*s* in the study area are rocky, shallow, with different mechanical composition and, according to laboratory analysis, are characterized as having low to medium fertility (humus in the 0–10–25 cm layer is 2.08–6.17%). The humus content (**Table 1**) is as follows: in the 0–25 cm layer it fluctuates within the range of 2.08–6.17%; total nitrogen 0.045–0.295%; phosphorus 0.080–0.190% and potassium 0.84–1.23%; the reaction of the soil solution is neutral to slightly alkaline – pH within the range of 7.30–8.55 (**Table 1**)[7,10].

Exposure dose in the tailings area and industrial sites. The conducted radiometric survey of the exposure dose rate of gamma radiation in various areas of uranium tailings and adjacent territories of Min-Kush showed a low level from 24 to 46 μR/h, but in some places, adjacent to man-made areas slightly increased to 60 μR/h, and in the territory where old coatings are destroyed, high on tailings, for example, on the Taldy-Bulak tailings 554–662 μR/h. Earlier, according to the results of research by individual experts, it was shown that the uranium content in the soil here, on average along the profile, fluctuates from 3.3 to $17.5 \cdot 10^{-6}$ g/g, i.e., quite high. The area above the enrichment plant is of great danger, where the uranium content in the soil reaches $30–35 \cdot 10^{-6}$ g/g at the surface, which indicates local contamination of this zone. In general, the soils of the Min-Kush geochemical province are significantly enriched with uranium, since the uranium concentration in them is 5–6 times higher than in the soils of Kyrgyzstan[7,23,24,29].

The content of radionuclides (U, Th, Ra, K) in soil covers before rehabilitation. The results of gamma-spectrometric analysis of soils of man-made objects in 2015 showed a significant amount of natural radionuclides ^{238} U and ^{26} Ra. **Table 2** shows that ^{238} U varies from 37.6 to 390.0 Bq/kg. The highest indicator of ^{238} U was noted at point MT2S2 (the body of the tailings dump "Taldy-Bulak"), which showed – 176.4 Bq/kg[10], at point MT4S2 (the body of the tailings dump "Dalniy") – 390.0 Bq/kg, at point M21S4 (adit on the territory of the 21st site) – 280.5 Bq/kg and MPS2 (territory of the old processing plant) – 251.4 Bq/kg.

On the studied soil samples, the ^{226} Ra indicator varies from 40 Bq/kg to 3591.7 Bq/kg. The highest indicator – 3591.7 Bq/kg was noted on the body of the tailings pond "Dalniy" (MT 4 S 2).

Table 2. Results of Gamma Spectrometric Analysis of Soils (2015).

Soil Sample Code	Sample Collection Location	Specific Activity, Bq/kg	
		^{238} U	^{226} Ra
MT S 1	Tailings dam "Tuyuk-Suu"	53.4 ± 6.0	149, 0 ± 2.2
MT1S2	Below 100 m from the Tuyuk-Suu tailings dump	56.2 ± 4.8	86.5 ± 5.3
MT2S2	Tailings dam "Taldy-Bulak"	176.4 ± 15.4	233.5 ± 13.5
MT 2S1	Below 100 m from the Taldy-Bulak tailings dump	48.9 ± 8.4	42.1 ± 1.9
MT3S2	Tailings "How"	97.7 ± 6.4	105.9 ± 6.3
MT 3S1	Below 100 m from the tailings pond "Kak"	77.1 ± 17.9	76.8 ± 3.1
MT4S2	Tailings storage facility "Dalniy"	390.0 ± 67.0	3591.7 ± 163.0
MT 4S1	Below 100 m from the tailings pond "Dalniy"	39.2 ± 5.0	82.8 ± 3.4
M17 S 1	Residential area No. 17	54.5 ± 5.7	68.4 ± 3.1
M21 S 1	Residential area #21	39.3 ± 6.8	40.8 ± 2.1
M PS2	Old enrichment plant	251.4 ± 26.2	298.0 ± 13.9
M DS 1	Residential area Dalniy Min-Kush	102.9 ± 17.8	99.1 ± 4.5

Our measurements indicate that native radionuclide concentrations in the sampled soils greatly surpass global background (Clarke) benchmarks: uranium is typically elevated by a factor of 10–15, radium by roughly 8–10, and in the Dalniy tailings area radium spikes to nearly 90 × the norm.

We measured and studied the doses of radionuclides ^{238}U, ^{232}Th, ^{226}Ra, ^{40}K in soil samples of tailings. The results of gamma spectrometric analysis at the point MST – 01 (the body of the tailings pond "Tuyuk-Suu") showed the specific activity of ^{238}U – 121.5 ± 15 Bq/kg, ^{226}Ra – 287.6 ± 29.16 Bq/kg, but the specific activity of ^{232}Th is higher than in other points, which showed 45.7 ± 3.68 Bq/kg, the specific activity of ^{40}K is 418 ± 26 Bq/kg (**Table 3**)[30].

Table 3. Results of Gamma-Spectrometric Analysis of Soils of Tailings Storage Facilities.

Sample Code	Sampling Location	r H	Specific Activity, Bq/kg							
			^{238}U	±	^{232}Th	±	^{226}Ra	±	^{40}K	±
MST-01-04	Tailings dump "Tuyuk-Suu"	8.20	121.5	15	45.7	3.68	287.6	29.16	418	26
MSTB-02-04	Tailings dump "Taldy-Bulak"	7.85	54.6	7	27.6	1.7	106.2	7.4	590	36
MSK-0 3 -04	Tailings storage facility "How"	8.35	203.3	25	33	2	991,0	31	483	25
MSD-0 4 -04	Tailings storage facility "Dalniy"	7.85	210.2	26	40.5	2,2	495.7	22	351	22
MSA-05-04	2 km below the village of Min-Kush	7.10	37.5	4	32	1.8	47.6	10	46	25
	Clark, Bq/kg		25		32.8		29.2		370	

Table 2 indicates that sampling point MSTB-02, located on the Taldy-Bulak tailings embankment, yielded a specific activity for ^{238}U of 54.6 ± 7 Bq kg^{-1}—somewhat lower than the figure recorded during the previous campaign. In the same horizon, ^{232}Th averaged 27.6 ± 1.7 Bq kg^{-1}, while ^{226}Ra reached 106.2 ± 7.4 Bq kg^{-1}. The strongest signal, however, came from ^{40}K, peaking at 590 ± 36 Bq kg^{-1}, the highest value among all surveyed sites.

At the tailings dump "Kak" (MSK-04) the specific activity is ^{238}U amounted to 203.3 ± 25 Bq/kg, and the ^{226}Ra indicator is 991.0 ± 31 Bq/kg, which constitutes the highest level of radionuclides in the soil of all points. The ^{232}Th indicator is–33.0 ± 2 Bq/kg, and the specific activity of ^{40}K is 483 ± 25 Bq/kg.

The highest values of ^{238}U and ^{226}Ra were recorded at the Dalniy tailings dump (point MSD-04): specific activity of ^{238}U – 210.2 ± 26 Bq/kg and ^{226}Ra – 495.7 ± 22 Bq/kg. The ^{232}Th indicator was 40.5 ± 2.2 Bq/kg and exceeds the geochemical background. The specific activity of ^{40}K showed 351 ± 22 Bq/kg.

The minimum radionuclide values were in soil samples from point MSA-05-04 (control point), where the specific activity of ^{238}U was 37.5 ±4 Bq/kg, ^{232}Th – 32 ±1.8 Bq/kg, ^{226}Ra – 47.6 ± 10 Bq/kg and ^{40}K – 46 ± 25 Bq/kg. **Figure 10** shows the obtained values of uranium series elements in soil samples of tailings dumps. It should be noted that, in general, our results correspond to the data of previously conducted researchers with some deviations[14,30–32].

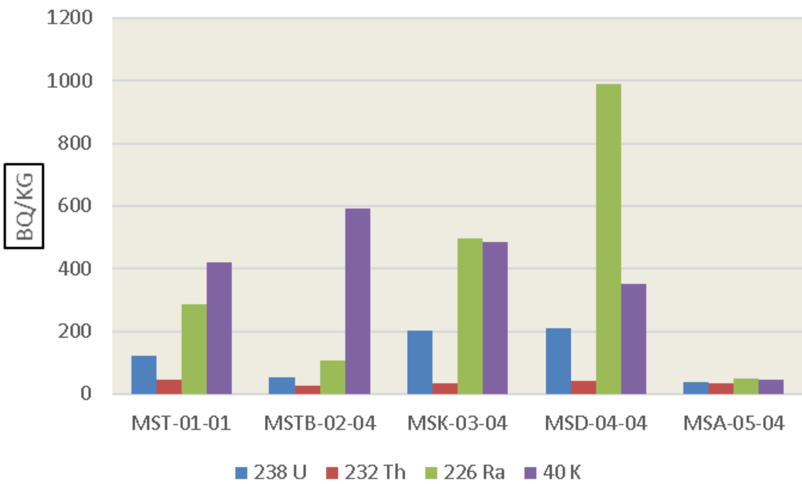

Figure 10. Comparative Specific Activity of Natural Radionuclides in the Tailings Dumps of the Village of Min-Kush.

In summary, soils taken from the tailings impoundments display natural radionuclide levels well above global background benchmarks: uranium is enriched roughly five- to eight-fold, radium about fifteen- to twenty-fold, and potassium by approximately 1–1.5 times the Clarke values.

Calculated data on the levels of radionuclide accumulation in reference organisms, embedded in the Erica tool 2 program database, showed that mosses and lichens are capable of accumulating more radionuclides compared to other organisms (**Figure 11** and **Table 4**). ^{226} Ra accumulates more intensively.

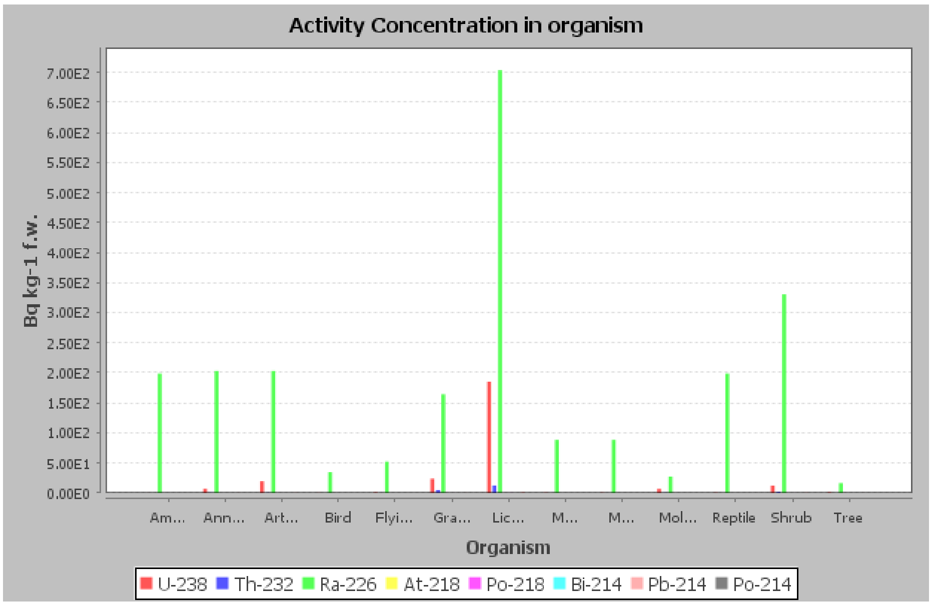

Figure 11. Calculated Data on the Levels of Accumulation of Radionuclides in Reference Organisms.

Table 4. The Value of Radiation Risk Coefficients for Mosses and Lichens.

Sampling Points	The Value of the Risk Coefficient for Radionuclides	Total Value of Risk Coefficient
Tailings dump "Tuyuk-Suu"	^{238} U – 0.95 ^{232} Th – 0.15 ^{226} Ra – 10.18	11.28
Tailings dump "Taldy-Bulak"	^{238} U – 0.42 ^{232} Th – 0.09 ^{226} Ra – 3.76	4.28
Tailings storage facility "How"	^{238} U – 1.58 ^{232} Th – 0.11 ^{226} Ra – 35.08	36.78
Tailings storage facility "Dalniy"	^{238} U –1.64 ^{232} Th – 0.14 ^{226} Ra – 17.55	19.32
2 km below the village of Min-Kush	^{238} U – 0.28 ^{232} Th – 0.11 ^{226} Ra – 1.68	2.07

According to the calculation results of this program, the maximum value of the risk coefficient for radionuclides is characteristic of the tailings storage facility "Kak" – 36.78. For radionuclides, high radiation risk coefficients are characteristic of ^{226} Ra – 35.08, lower ones for ^{238} U – 1.58 and ^{232} Th – 0.11 (**Table 4**).

5. After Rehabilitation Work

During rehabilitation work, radiation monitoring was constantly carried out in the environmental objects. **Table 5** shows the average value for 3 months during the work—gamma radiation dose rate, radon, suspended particles in the air, radioactive dust settling and a measurement map is compiled (**Table 5**). As an example, a map of the ore warehouse area before and after rehabilitation is shown (**Figures 12–14**).

Table 5. Measurement of Radiation Dose on Site (at the Industrial Site and Workplaces During Work).

Monitoring from 09.11.2020 to 14.02.2021				
Physical Quantities	**Frequency and Equipment**	**Date of Measurement/ Sampling**	**Places and Results**	**Above the Level of Intervention**
Measuring the dose rate of gamma radiation (10)	1 мabove ground level, (Industrial zone)	09/11/2020 14/02/2021	0.15-0.28 μSv/h	(2 μSv/h)
Radon and radon decay products	Weekly measurements using portable monitors (Industrial zone)	09/11/2020 14/02/2021	Office, Industrial zone ERVA=10–15 Bq/ ^{m3}	150 Bq/m³
Suspended particles in the air	Dust analyzer "Atmas" No. 37120 for PM10,	09/11/2020 14/02/2021	Industrial zone (workplace) PM $_{10,}$ – (30–100 μg/m³)	PM $_{10}$, 500 μg/m³
Radioactive dust/long-lived alpha particles	Mixed sample consisting of 4 weekly samples	09/11/2020–18/12/2020	Total alpha activity α=0.11 mBq/ ^{m3} Specific activity Po-210 = 0.084 mBq/m³	Long-lived alpha particles, 5 mBq/m³
Settling of radioactive dust	Bergerhoff banks were installed at the construction site in the direction of the winds, time – 1 month	09/11/2020–18/12/2020	Specific activity Po-210 = 0.033 Bq/ (m ^{2} day)	Sedimentation rate Ra-226, 5 Bq/(m² 30 days)

Figure 12. Industrial Site (in the Process of Reclamation).

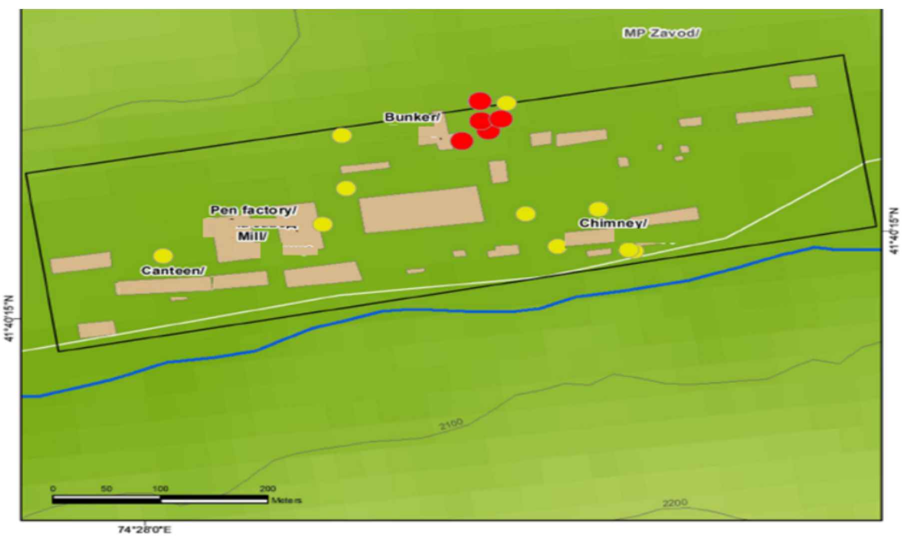

Figure 13. Radiation Background of an Industrial Site Before Reclamation.

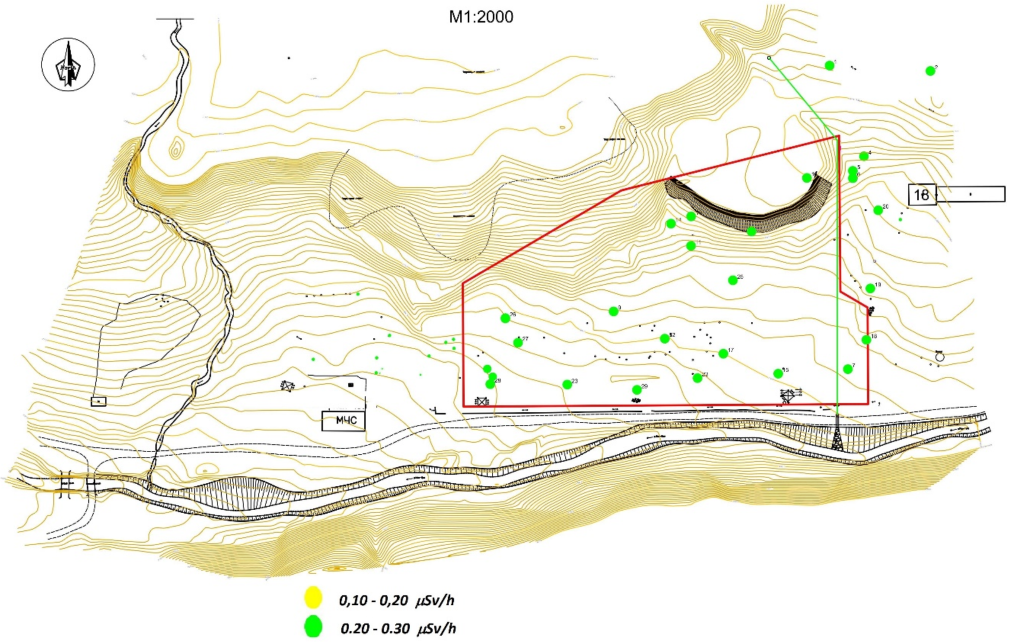

Figure 14. Radiation background of an Industrial Site After Reclamation.

It is known that there are two types of potentially vulnerable people during the remediation of contaminated sites: members of the public and workers at remediation sites.

Evaluation criteria:

- The general annual effective dose limit for the population is 1 mSv
- The general annual effective dose limit for workers is 20 mSv
- Annual dose from drinking water – 0.1 mSv (reference level)

As a rule, doses for the population and workers are very low for the type of reclamation work performed, given the low level of specific activity of the objects and materials being moved in the province. Reclamation work was also carried out on individual contaminated sites (industrial site, ore warehouses, etc.) (**Figures 12–17**). During the reclamation process, daily and monthly measurements of background radiation concentrations were taken (**Table 6**).

Figure 15. Ore Stockpile Before Reclamation (Decomposition Process).

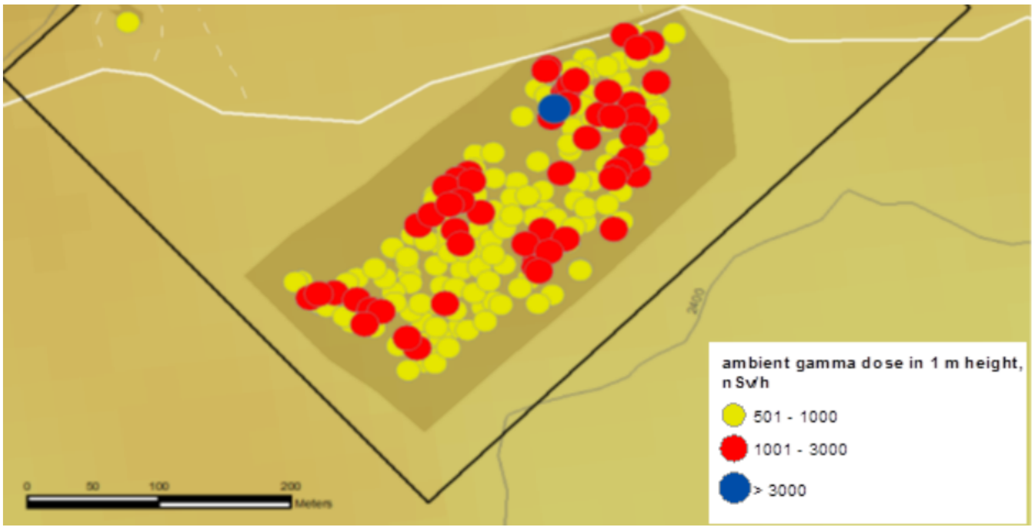

Figure 16. Map-Scheme of the Ore Warehouse Before Covering (Reclamation).

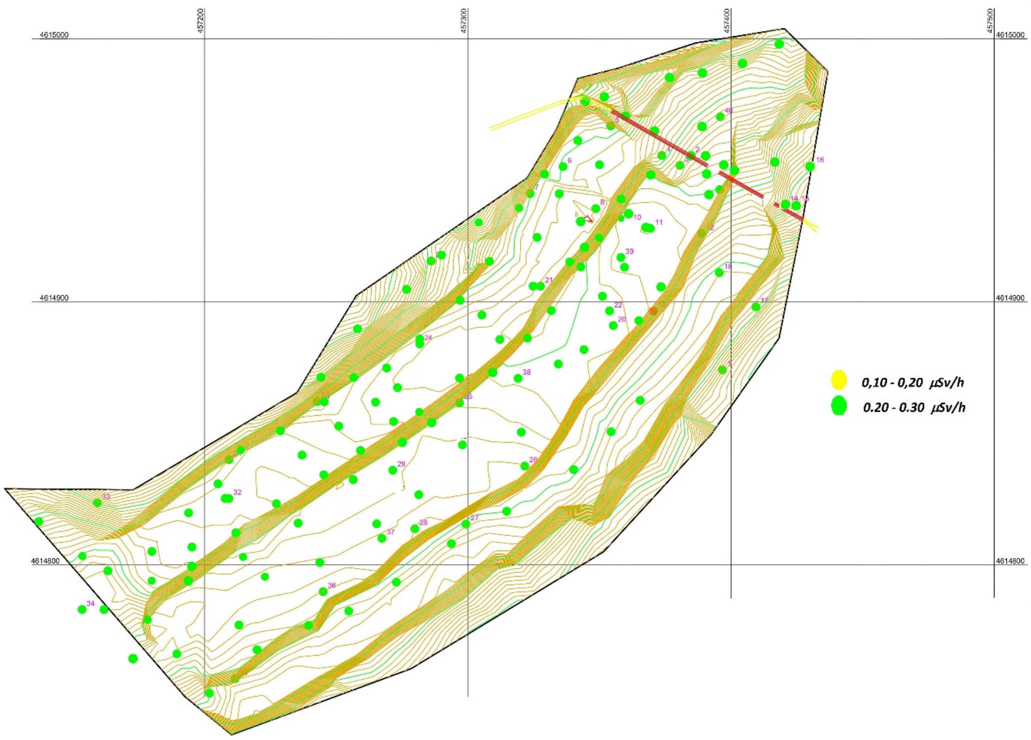

Figure 17. Map-scheme of the Ore Warehouse Area After Covering (Reclamation).

From **Figures 12–14** it is seen that all industrial buildings and structures and adjacent contaminated territories are developed according to the approved reclamation projects and the corresponding international IAEA requirements. Before reclamation there was an increased value of the exposure dose in almost all industrial areas (upper layers of soil cover, old buildings, etc.), as shown in **Figure 13** from 1000 to 3000 nSv/h, which is higher than the accepted standard in the country, as well as the IAEA standard. In **Figure 14** the radiation background in industrial areas and the Ore warehouse (10 s) after reclamation showed that the level of the exposure dose corresponds to the accepted standard and is at the background level in this area.

Table 6. KW 0 Weekly Monitoring 5, SK Alliance.

Monitoring Industrial Zone (outside Construction Sites)				
Physical Quantities	**Frequency and Necessary Equipment**	**Date Measurements / Samples Selection**	**Place Measurements and Results**	**Exceeding Level Interventions**
Measurement power gamma- H *(10) radiation	1 m over level lands, sensitivity device 50 n3v/h - 100 µ3v/h), daily inspection in the representative construction zone (industrial zone) DKS-96, factory number 766	25/01/2021	0.2–0.27 µ3v/h	increases level interventions (2 µ3v/h) Not discovered
		26/01/ 2021	0.12–0.26 µ3v/h	Not discovered
		27/01/2021	0.15–0.24 µ3v/h	Not discovered
		28/01/2021	0.14–0.26 µ3v/h	Not discovered
		29/01/2021	0.18–0.24 µ3v/h	Not discovered
		30/01/2021	0.12–0.25 µ3v/h	Not discovered
		31/01/2021	0.14–0.26 µ3v/h	Not discovered
Inspection	Place measurements and results			
Zone interest	Regularity inspections	Date measurements/ sampling		Not discovered
Enter/Exit radioactive for the dirty one material	Daily visual inspection (p. rom. z on)	25/01/2021		Not discovered
		26/01/2021		Not discovered
		27/01/2021		Not discovered
		28/01/2021		Not discovered
		29/01/2021		Not discovered
		30/01/2021		Not discovered
		31/01/2021		Not discovered
Strait fuel	Daily visual inspection jobs and transport roads	25/01/2021		Not discovered
		26/01/2021		Not discovered
		27/01/2021		Not discovered
		28/01/2021		Not discovered
		29/01/2021		Not discovered
		30/01/2021		Not discovered
		31/01/2021		Not discovered
Strait Fuel and lubricants	Daily visual inspection (p r o m zone)	25/01/2021		Not discovered
		26/01/2021		Not discovered
		27/01/2021		Not discovered
		28/01/2021		Not discovered
		29/01/2021		Not discovered
		30/01/2021		Not discovered
		31/01/2021		Not discovered

Source: By object "Min-Kush" from 25–31 January 2021. (Daily regulations).

6. Conclusions

Kyrgyzstan's current remediation campaign directly targets the environmental legacy of decades-old mining and milling. A coordinated, nationwide programme now tackles dozens of hotspots where vast quantities of radioactive and chemically hazardous waste were once stockpiled, thereby lowering long-term risks for ecosystems and human health.

Mountain geomorphology amplifies those risks: gullying, debris flows, seismic shaking and seasonal floods can remobilise contaminants far beyond their original footprints—especially because many tailings impoundments and waste dumps flank river corridors. Protective measures around these watercourses, however, still lag behind modern best practice.

Although the republic has adopted a solid legal framework for resource stewardship and pollution control, implementation on the ground remains uneven. In Min-Kush, for example, quarrying stripped vegetation and soil, accelerating industrial erosion and leaving slopes exposed to wind and water attack. Field and laboratory surveys have documented both naturally driven and anthropogenic degradation processes.

Local testimony points to a rise in landslides after major rain- and snowstorms. Given that one tailings pile sits only a few metres from the Tuyuk-Suu channel, a slide capable of damming the river would threaten a sudden wash-out of radioactive sediments. To pre-empt this scenario, high-risk materials have been relocated and sealed at safer locations. The Ministry of Emergency Situations, the national tailings-management authority and several international donors supplied the technical and financial muscle for these operations. Reclamation of the ore stockyard and other critical sub-sites (plots 17, 21, etc.) has been completed in compliance with both Kyrgyz and IAEA radiation-safety standards.

Dormant tailings structures nevertheless remain latent pollution sources; without ongoing upkeep they could deteriorate into chronic emitters of radionuclides and toxins. Continuous surveillance, contingency planning and rapid-response capacity are therefore essential to safeguard people, biota and infrastructure while keeping future remediation costs manageable.

Author Contributions

All authors made significant contributions to this study. B.D. developed the study concept; Z.D. and M.R. developed the methodology; B.Z. contributed to data collection and resources; A.M. supervised the data; T.D. prepared the initial draft, and B.D. and Z.D. reviewed and edited the manuscript. B.Z. supervised the study. All authors have read and approved the final manuscript.

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Not applicable.

Data Availability Statement

Our data is open, so we publish it openly in the journal. Some of our references to literary sources are only available in paper form and there are no electronic versions.

Conflicts of Interest

All the authors declare that there is no conflict of interest in relation to the research, authorship, and publication of this study.

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