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ENVIRONMENTAL ASPECTS OF RADIONUCLIDE CONTAMINATION OF THE OKCHUCHAY TRANSIT RIVER IN THE REPUBLIC OF AZERBAIJAN

Ramil Ali Sadigov[1], **Yusif Zaur Valiyev**[2*]
[1]Azerbaijan State University of Economics, Baku, Azerbaijan
[2]Shaki, Shaki Chemistry-Biology Biased Lyceum, Shaki, Azerbaijan
*josephveliyev@gmail.com
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Radionuclide contamination is becoming a significant environmental concern, especially in transboundary rivers such as the Okchuchay, which flows through the Republic of Azerbaijan and Armenia. This study evaluates the extent, sources, and impacts of radionuclide contamination in the Okchuchay River, focusing on cesium-137, strontium-90, uranium, and thorium. Extensive field sampling and analytical techniques reveal contamination levels posing serious risks to ecosystems and human health. The findings call for effective regulation, international cooperation, and innovative remediation strategies, including phytoremediation and advanced wastewater treatment. By synthesizing lessons from contamination cases such as Chernobyl and Fukushima, this study provides actionable recommendations for mitigating radionuclide pollution in the Okchuchay River and similar transboundary water systems.

Keywords: *environment, ecological aspects, radionuclide contaminations, river ecosystem, Okchuchay.*

INTRODUCTION

Radionuclide contamination is a major environmental issue with long-term effects on ecosystems and human health. This problem is particularly concerning in transboundary water systems where pollutants cross national borders, complicating remediation efforts. The Okchuchay River, a transit river in the Republic of Azerbaijan, has drawn increasing attention due to rising concerns about radionuclide contamination [20]. The Okchuchay River is vital for both Armenia and Azerbaijan, flowing through economically and ecologically important areas. However, its role as both a natural watercourse and an industrial waste conduit highlights the urgency of addressing pollution from upstream industrial activities. Specifically, Armenia's mining operations in Kapan and Kajaran release significant quantities of heavy metals and radionuclides into the river, threatening its ecological balance and the health of downstream communities [3-4]. This study explores the sources, impacts, and mitigation strategies for radionuclide contamination in the Okchuchay River, emphasizing the need for international cooperation and strict environmental policies [1].

Picture 1: Kapan region

Picture Source: news.am – "News Article 312482" [accessed from news.am/eng/news/312482.html]

Environmental aspects

The environmental impact of radionuclide contamination in the Okchuchay River is extensive, affecting aquatic ecosystems, soil health, and biodiversity [3, 21]. Extensive research indicates that the accumulation of radionuclides is strongly influenced by the physicochemical properties of water and sediments, which facilitate the binding of contaminants to fine particulates [11].

1. Aquatic Ecosystems: Radionuclides such as cesium-137 and strontium-90 accumulate in aquatic organisms, disrupting food chains and reducing biodiversity. Sediment-bound radionuclides degrade water quality, making the river uninhabitable for many species [6].
2. Soil Contamination: Irrigation with contaminated water leads to radionuclide accumulation in agricultural soils, altering soil chemistry and reducing fertility. Long-lived radionuclides such as uranium remain in the soil, complicating land restoration [13].
3. Cross-border Pollution: The transboundary nature of the Okchuchay exacerbates environmental challenges, as contaminants released upstream Armenia impact downstream ecosystems and communities in Azerbaijan, requiring international intervention [8].
4. Long-term Persistence: Radionuclides persist in the environment for decades or even centuries, necessitating sustainable management strategies to minimize long-term damage [21].

Overview of the Okchuchay river

The Okchuchay River, also spelled Oxçuçay, is a tributary of the Aras River and flows through both Armenia and Azerbaijan. It originates from the Zangezur mountain range at Mount Kaputjugh at an elevation of 3,285 meters. The river spans a length of 85 kilometers and has a drainage basin of 1,140 square kilometers. Hydrologically, the river's flow is supported by snowmelt (46%), groundwater (44%), and rainfall (10%). The river experiences a very strong seasonal flow variation, with the highest flows occurring during spring and summer, accounting for more than 80% of the annual flow. On average, a river discharge of 8.90 cubic meters per second is measured.

In the Zangilan district of Azerbaijan, it plays a vital role in irrigation and in the supply of local water. Its ecological sustainability and economic potential have been highly compromised by industrial pollution coming from upstream (Picture 1). The stretch of the river in Armenia, referred to as the Voghji River, receives huge amounts of industrial wastes from mining and metallurgical industries.

Picture 2: The Okchuchay River

Picture Source: Aze.Media. "The Okchuchay River's Plight Amidst Cross-Border Pollution." Published February 21, 2024. Retrieved from https://aze.media/the-okchuchay-rivers-plight-amidst-cross-border-pollution/.

MATERIAL AND METHODS

With a view to study the extent and effects of radionuclide contamination in the Okchuchay River, some complex field samplings were performed, along with analytical methodologies. This section describes the strategy of sampling, laboratory analysis, and data interpretation techniques [14].

Study area and sampling

Water, sediment and biota were collected from multiple sites along the Okchuchay River (upstream, midstream and downstream segments) to assess spatial variation. Sampling was carried out in different seasons (e.g. spring and autumn) to capture hydrological differences. At each site, surface-water grab samples (~1–2 L) were collected in pre-cleaned, acid-washed polyethylene bottles. Sediment samples (~1 kg) were taken from the river bed (top ~0–10–20 cm) using a stainless-steel grab sampler. Selected biota (aquatic plants and/or fish) were also collected by netting or hand-picking, rinsed with deionized water, and stored in clean containers. Water samples were immediately filtered through 0.45 µm membrane filters and acidified to pH ≈2 (using concentrated HNO_3) to preserve dissolved radionuclides. Sediments were kept cool and biota samples were stored frozen during transport. GPS coordinates were recorded for each sampling point to enable spatial mapping.

Sample preparation

In the laboratory, water samples were mixed and aliquots were prepared for analysis. Sediment and biota samples were oven-dried (110°C) to constant weight. Large debris and stones were removed by sieving (stones >5 mm discarded). Dried sediments were gently disaggregated and ground (to ~0.5–2 mm particle size), then homogenized in an agate mortar. Aliquots of sediment (typically 200–300 g) and biological tissue were then ashed in a muffle furnace: the temperature was slowly raised to ~300 °C and held, then heated to 600 °C for several hours to remove organic matter. The ash was weighed and digested in acid as needed for radionuclide extraction. For example, ash or sediment powders were treated with concentrated HNO_3 (and HF when required) under reflux or microwave digestion. After digestion, samples were evaporated to near-dryness and reconstituted in appropriate dilute acid. Sub-samples of processed material were retained to determine moisture content and for repeat analyses. All sample containers and bottles had been pre-soaked in 5% HNO_3 and rinsed with ultra-pure water prior to use

Analytical techniques

A combination of radiometric and spectrometric methods was used:

- **Gamma spectrometry (HPGe):** Gamma-emitting radionuclides (e.g. ^137Cs, ^40K, U/Th decay products) were measured using high-purity germanium (HPGe) detectors (coaxial, low-background) in a shielded counting chamber. Efficiency calibrations were performed with standard multi-nuclide sources in the same geometry as samples. Spectra were collected until the statistical uncertainty was <5%. This approach follows established practice.
- **Inductively Coupled Plasma Mass Spectrometry (ICP-MS):** Non-radioactive elements (and total U and Th concentrations) were determined by ICP-MS. An Agilent 7700 quadrupole ICP-MS (USA) was used under standard operating parameters (RF power ~1300 W, gas flows, etc.). Samples were introduced via a quartz nebulizer into an argon plasma. Multi-element calibration standards (NIST traceable) were run bracketing sample concentrations.
- **Alpha spectrometry:** Long-lived alpha emitters (e.g. ^238U, ^234U, ^232Th, ^230Th, ^210Po) were measured by alpha-particle spectrometry after radiochemical separation. For example, U/Th was separated by anion-exchange and micro-precipitated onto stainless steel disks, then counted in a vacuum alpha-spectrometer. The sample processing followed standard procedures (tracers added, coprecipitation, electrodeposition). Although no direct citation is given here, this method is routine for environmental U/Th analysis.
- **Liquid Scintillation Counting (LSC):** β-emitting radionuclides were measured by LSC. Tritium (^3H) in water was determined by distilling a fraction of the acidified sample (preventing Rn or ^14C carryover) and counting the collected fraction in scintillation cocktail. Strontium-90 (^90Sr) was analyzed by first separating Sr via a Sr-specific resin (e.g. Sr-Spec) after Ca-phosphate coprecipitation. The purified ^90Sr (and ^90Y daughter) was then

mixed with scintillator and counted. Calibration for LSC efficiency was done using ^3H and ^90Sr/^90Y standards.
- **Screening for gross α/β:** As recommended by WHO, an initial screening of gross alpha and beta activity was performed by evaporating aliquots of water on planchets and counting the residues (P-type Si(Li) detector for α, gas-flow counter for β). This allowed quick identification of samples exceeding WHO screening levels (α >0.5 Bq/L, β >1 Bq/L).

Calibration and Quality Control

All instruments were calibrated against certified reference materials. For gamma spectrometry, energy calibration used mixed gamma sources and efficiency was checked using IAEA reference soils and water standards. For ICP-MS, calibration curves were generated from multi-element standards. Radiochemical yields were monitored by adding known tracer nuclides (e.g. ^236Pu, ^242Pu, ^243Am for actinide series; stable Sr carrier for ^90Sr) before chemical separation. System blanks, laboratory blanks and duplicate splits were analyzed with each batch to check for contamination or loss. Duplicate and triplicate analyses were routinely performed (especially for key samples) as part of QA/QC. Internal precision (replicates) was typically <5–10%. The accuracy was verified by analyzing certified reference materials (river water, sediment) and by inter-laboratory comparisons. All results were checked against international guidelines: for example, measured water concentrations were compared to WHO drinking-water reference levels. Quality assurance followed IAEA and WHO recommendations for radionuclide monitoring in the environment, including documentation of procedures and data quality.

Data analysis and mapping

Activity concentrations were decay- and background-corrected. Spatial distribution maps were created using GIS software to visualize trends along the river. Statistical analyses were performed using software (e.g. R or SPSS). One-way ANOVA (and non-parametric tests, as appropriate) tested for significant differences among sites and seasons (significance at $p<0.05$). If data did not meet normality assumptions, Kruskal–Wallis tests were applied. Trends in radionuclide levels were evaluated both qualitatively and by regression analysis. Finally, all measured concentrations were interpreted against international safety standards (WHO Guidelines for Drinking Water Quality and IAEA criteria) to assess compliance and potential risk.

Sources and Causes of Contamination

The principal sources of radionuclide pollution of the Okchuchay River are mining operations in the Armenian regions of Kapan and Kajaran (Picture 2) [10, 11]. There are large-scale mining activities, particularly in the extraction of copper and molybdenum, with resultant huge masses of tailings and wastewater. Very often, these by-products contain radioactive substances like uranium, thorium, cesium-137, and strontium-90 [2]. Due to poor treatment and disposal methods, these contaminants find their way into the river ecosystem.

Other than the mining activities, natural processes make a large contribution to the dispersion of radionuclides [9]. Erosion, leaching, and sediment transportation during seasonal flooding encourage downstream dispersal of radioactive materials. These radionuclides tend to sorb onto fine particulate matter, which makes remediation processes difficult and prolongs environmental exposure time [18].

RESULTS AND DISCUSSION

Spatial and Temporal Distribution of Radionuclides

Field analysis along the Okchuchay River revealed a distinct spatial gradient in radionuclide concentrations. Upstream areas near Armenia showed relatively moderate contamination levels, while midstream and particularly downstream sites—especially those in Azerbaijan's Zangilan district—exhibited significantly higher levels of cesium-137 (^137Cs), strontium-90 (^90Sr), uranium (U), and thorium (Th) [11, 21]. This distribution aligns with the known industrial discharge zones in Kapan and Kajaran, Armenia, where heavy mining of copper and molybdenum takes place [2].

Seasonal monitoring showed radionuclide concentrations peaking during spring and early summer, coinciding with snowmelt and increased discharge [21]. These seasonal fluctuations promote mobilization of contaminated sediments and enhance downstream transport.

Radionuclide Behavior in Environmental Matrices

Each radionuclide exhibited specific environmental behavior depending on its chemical properties:

- **Water samples** had elevated levels of ^137Cs and ^90Sr at mid- and downstream sites, in some cases exceeding WHO safety thresholds [World Health Organization, 2021].
- **Sediments** were the primary sink for uranium and thorium due to their strong affinity for fine particles [20].
- **Biota**, such as fish and aquatic plants, accumulated ^137Cs and ^90Sr via trophic transfer, posing serious ecological and human health risks [12].

Similar behavior has been documented in post-accident river systems around Chernobyl and Fukushima, where radionuclides remained persistent in sediments and bioaccumulated in aquatic food chains [22].

Comparison to International Case Studies

A comparative analysis shows Okchuchay's contamination profile resembles Chernobyl and Fukushima in key aspects (table 1). While Okchuchay's radionuclide sources are industrial rather than nuclear, environmental consequences are comparable and warrant urgent mitigation [9].

Table 1.

Comparison of Radionuclide Impacts in Different Regions

Region	Primary Radionuclides	Key Impacts	Mitigation Strategies
Okchuchay	Cesium-137, Uranium	Loss of biodiversity, contaminated water	Advanced treatment, phytoremediation
Chernobyl	Cesium-137, Strontium-90	Soil contamination, health risks	Buffer zones, waste containment
Fukushima	Cesium-137, Iodine-131	Long-term agricultural impact	Soil washing, community engagement

Source: [21]; retrieved from Anthropocene, DOI: 10.1016/j.ancene.2013.07.001. Note: The information in this table is based on comparative studies of nuclear contamination events worldwide.

Ecological Impacts

The river's ecological integrity is under severe threat. Observed effects include:

Aquatic biodiversity collapse due to toxic concentrations (table 2) of ^137Cs, ^90Sr, and heavy metals [12, 21]

Disruption of food chains, especially among primary producers and consumers [5].

Sediment-bound contamination hotspots, which continue releasing radionuclides over time [18].

This mirrors conditions observed in the Dnieper and Danube Rivers, where fine sediments acted as long-term reservoirs for contamination [22].

Table 2.

Key Radionuclides in the Okchuchay River

Radionuclide	Source	Environmental Impact	Health Risks
Cesium-137	Mining tailings, industrial waste	Bioaccumulates in aquatic organisms	Increases cancer risk, genetic mutations
Strontium-90	Mining, soil erosion	Binds to sediments, affects soil fertility	Accumulates in bones, causes leukemia
Uranium	Mining activities	Contaminates groundwater	Kidney damage, carcinogenic
Thorium	Industrial discharge	Persistent in soil and water systems	Carcinogenic

Note: The data presented in this table are based on environmental monitoring reports and scientific studies conducted in the Okchuchay River region.
Source: [21]; retrieved from the PANGAEA dataset (https://doi.org/10.1594/PANGAEA.928594) .

Agricultural and Human Health Risks

The use of contaminated Okchuchay water for irrigation introduces radionuclides into agricultural soils, from which they can be taken up by crops (table 2) [15]:

- **Uranium and thorium** disrupt soil microbial balance, reducing fertility [11].
- **^90Sr**, being chemically similar to calcium, accumulates in human bone tissue, increasing the risk of leukemia [22].
- **^137Cs**, similar to potassium, concentrates in muscles and organs, raising soft tissue cancer risks [23].

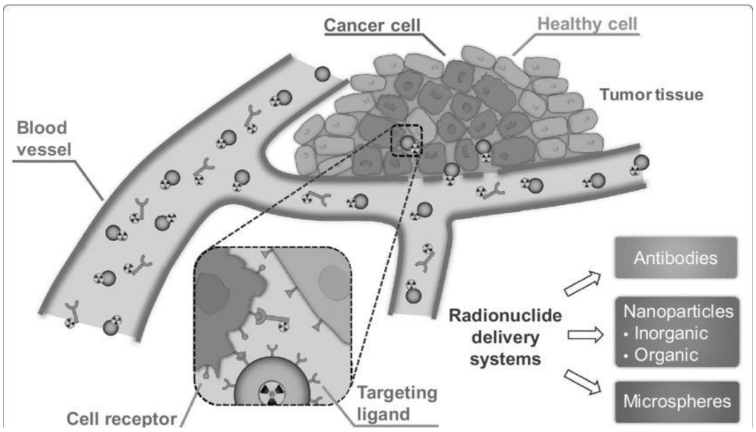
Populations in the Zangilan region are at heightened risk due to chronic exposure through drinking water, food, and skin contact [7, 16].

Implications and Recommendations

Based on the findings: Joint Armenian-Azerbaijani environmental monitoring should be initiated under international frameworks [17, 19].

- **Phytoremediation** with species like *Helianthus annuus* (sunflower) and *Brassica juncea* (Indian mustard) has proven successful post-Chernobyl and can be implemented in Okchuchay [9].
- **Sediment dredging and stabilization** with phosphate compounds or biochar should be considered at identified hotspots [18].
- **Public health screening** and cancer surveillance must be initiated downstream [23].

International regulatory support (similar to the Danube Convention) could ensure data transparency, cross-border cooperation, and enforcement [7].

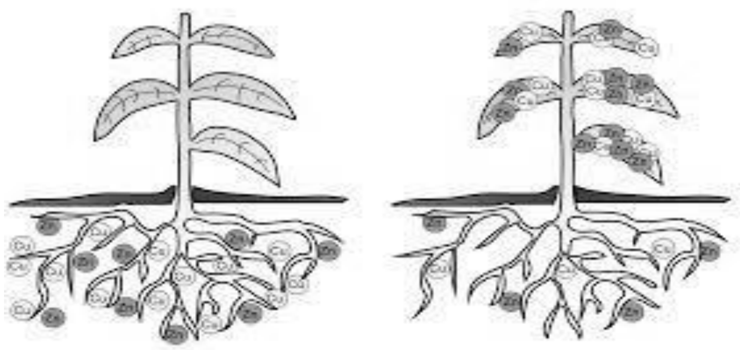


Picture 3. The cases of cancer

Source: [23]. Current outlook on radionuclide delivery systems: from design consideration to translation into clinics. Journal of Nanobiotechnology, 17, 90.

Proposed Mitigation Strategies. Mitigation strategies for radionuclide contamination include:

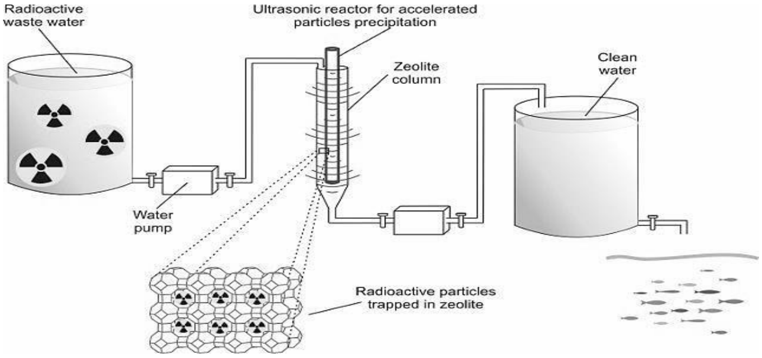
1. Phytoremediation: The use of hyperaccumulator plants like *Helianthus annuus* (sunflower) and *Brassica juncea*(Indian mustard) to extract and stabilize radionuclides. This method, initially proposed by Chaney [1983], has been successfully applied in Chernobyl and Fukushima. For instance, after the Chernobyl disaster, sunflowers were planted in contaminated water bodies to absorb cesium-137 and strontium-90, demonstrating phytoremediation's potential for large-scale remediation [9, 24] (Picture 3, 4).
2.



Picture 4. Phytoremediation

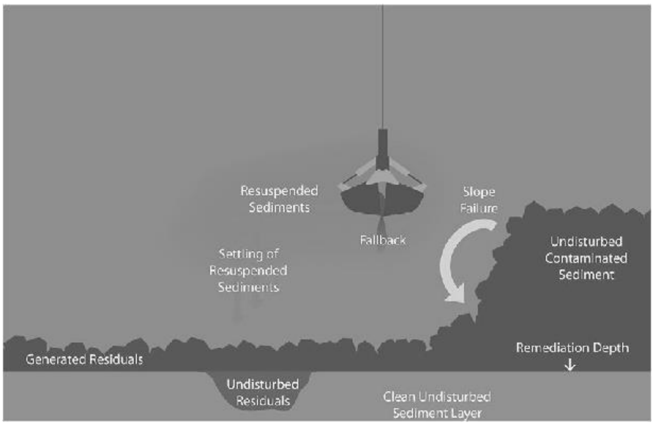
Source: Wikipedia – "Phytoremediation." Retrieved from Wikipedia

3. Advanced Wastewater Treatment: Reverse osmosis and ion exchange techniques have been effectively used to remove radionuclides from wastewater. These technologies were first implemented in nuclear facility effluent treatment during the 1970s and have since been widely applied in industrial wastewater management. For example, the treatment of mining effluent in the Colorado River Basin successfully reduced uranium and heavy metal concentrations, providing a model for Okchuchay's remediation [7] (Picture 5).



Picture 5. Waterman Australia - "Ion Exchange Treatment of Radioactive Wastewater."
Source: Retrieved from Waterman Australia

3. Sediment Dredging and Stabilization: Removing contaminated sediments from riverbeds has been a proven method in large-scale cleanup projects. The Hudson River cleanup project demonstrated the effectiveness of dredging in removing PCB-contaminated sediments. Similarly, adding biochar and phosphate compounds to stabilize contaminants in river sediments has been successfully tested in the Danube River region [18] (Picture 6).



Picture 6. Sediment Dredging

Source: [24]. Environmental Dredging Residual Generation and Management. Integrated Environmental Assessment and Management, 14. https://doi.org/10.1002/ieam.4032.

4. International Agreements and Policy Enforcement: Regulatory measures and international-cooperation play a crucial role in mitigating transboundary pollution. The European Union's Water Framework Directive has been instrumental in reducing industrial waste discharge across member states. A similar agreement between Azerbaijan and Armenia, modeled after the Danube River Protection Convention, could lead to improved monitoring, pollution control, and long-term remediation efforts [17].

CONCLUSION

The Okchuchay River is a vivid example of the disastrous ecological consequences of uncontrolled industrial activity. In particular, radionuclide pollutants give a twofold threat to both the ecosystems of the river and the health and livelihood of its adjacent populations.Urgent interventions are needed to reduce these negative impacts through strengthened regulatory frameworks, global cooperation, and active participation by the community. It will also draw on the experience of similar incidents around the world, such as Chernobyl and Fukushima , to develop a broad long-term plan for the remediation and restoration work on the Okchuchay River and its surroundings

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AZƏRBAYCAN RESPUBLİKASINDA OKÇUÇAY TRANZİT ÇAYININ RADIONUKLİDLƏ ÇİRKLƏNMƏSİNİN EKOLOJİ ASPEKTLƏRİ

R.Ə. Sadıqov, Y.Z. Vəliyev

Radionukloid çirklənməsi, xüsusilə Azərbaycan və Ermənistan ərazilərindən axan transsərhəd çaylar, o cümlədən Oxçuçay üçün ciddi ekoloji problemə çevrilməkdədir. Bu tədqiqat Oxçuçay çayında radionukloid çirklənməsinin miqyasını, mənbələrini və təsirlərini qiymətləndirir və əsas diqqəti sezium-137, stronsium-90, uran və torium elementlərinə yönəldir. Aparılan sahə tədqiqatları və analitik üsullar çirklənmə səviyyələrinin ekosistemlər və insan sağlamlığı üçün ciddi risklər yaratdığını göstərmişdir. Nəticələr effektiv tənzimləmə, beynəlxalq əməkdaşlıq və fitoremediasiya, qabaqcıl tullantı sularının təmizlənməsi kimi innovativ təmizləmə strategiyalarına ehtiyac olduğunu vurğulayır. Çernobıl və Fukusima kimi çirklənmə hadisələrindən çıxarılan dərsləri nəzərə alaraq, bu tədqiqat Oxçuçay və digər transsərhəd su hövzələrində radionukloid çirklənməsinin azaldılması üçün praktiki tövsiyələr təqdim edir.

Açar sözlər: *ətraf mühit, ekoloji aspektlər, radionukloid çirklənməsi, çay ekosistemi, Oxçuçay.*

ЭКОЛОГИЧЕСКИЕ АСПЕКТЫ РАДИОНУКЛИДНОГО ЗАГРЯЗНЕНИЯ ТРАНЗИТНОЙ РЕКИ ОКЧУЧАЙ В АЗЕРБАЙДЖАНСКОЙ РЕСПУБЛИКЕ

Р.А. Садыгов, Ю.З. Велиев

Радионуклидное загрязнение становится серьезной экологической проблемой, особенно в трансграничных реках, таких как Окчучай, протекающая через Республику Азербайджан и Армению. В этом исследовании оцениваются масштабы, источники и последствия радионуклидного загрязнения реки Окчучай, уделяя особое внимание цезию-137, стронцию-90, урану и торию. Обширные полевые отборы проб и аналитические методы выявляют уровни загрязнения, представляющие серьезные риски для экосистем и здоровья человека. Результаты требуют эффективного регулирования, международного сотрудничества и инновационных стратегий рекультивации, включая фиторемедиацию и современную очистку сточных вод. Обобщая уроки из случаев загрязнения, таких как Чернобыль и Фукусима, это исследование дает действенные рекомендации по смягчению загрязнения радионуклидами в реке Окчучай и аналогичных трансграничных водных системах.

Ключевые слова: *окружающая среда, экологические аспекты, радионуклидное загрязнение, речная экосистема, Окчучай.*