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Assessment of the hazard risk of the Metsamor Nuclear Power Plant (NPP) in Nakhchivan autonomous republic

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ABSTRACT

Problem Statement. Although nuclear power plants are considered to be a more economically efficient type of energy, they are considered a source of environmental danger in many respects. The Metsamor Nuclear Power Plant (Armenia) is one of the main sources of environmental risk, contributing not only to ecological problems in the area of its location within Armenia but also to transboundary impacts on neighboring countries, particularly affecting the Nakhchivan Autonomous Republic (Azerbaijan), as well as Eastern Anatolia (Türkiye), western Iran and parts of the South Caucasus (Georgia, Armenia, and Azerbaijan).

The aim of this study. The aim of the study is to study atmospheric dispersion processes, The aim of the study is to assess the environmental impact of radioactive discharges, in relation to the location of MNPP reactors in a high seismic-risk border region, and to investigate the possible transport of pollutants to the Nakhchivan Autonomous Republic via air currents and the Aras River.

Research Methodology. The study covers a spatial analysis of transboundary radioecological hazards in the Aras River basin, based on the collection of hydroecological samples in the field, laboratory analysis of water and ichthyofauna, geoinformation mapping, and a comprehensive assessment of seismotectonic risks. Physico-chemical, microbiological and biological parameters (pH, heavy metals, nitrates, phosphates, oxygen content, etc.) were investigated in water samples, and fish were used as bioindicators to assess the long-term accumulation of radionuclides. Furthermore, using ArcGIS (ArcMap) software, the risk factors of tectonic processes that have occurred and could occur in the area were studied, and an ecological zoning map of the Nakhchivan Autonomous Republic portion of the Aras River basin was prepared.

Scientific novelty of the research. For the first time, the radiological risk associated with the Metsamor NPP has been assessed in the Nakhchivan Autonomous Republic based on an integrated regional analysis of atmospheric transport, riverine dispersion, and the biological migration of radioisotopes. In recent years, ecological zoning has been carried out and a map has been prepared, illustrating the impact of the Metsamor NPP on the Aras River basin and the Aras reservoir.The novelty of the study is characterised by the development of a spatial model of transboundary ecological risk in the Aras River basin, based on the integration of hydrochemical indicators, biotic accumulation data, and seismic hazard analysis.

Results. The study determined that the main pathways of radionuclide dispersal are the Aras River, atmospheric circulation, and fish migration. Taking into account the potential dispersion of radioactive waste in the basin, the area's rivers were divided into three categories based on their ecological condition: clean, relatively clean, and highly polluted. A map compiled using ArcMap confirms the area's seismic risk, showing that hundreds of earthquakes with a maximum magnitude of 7 have been recorded in the last 45 years since the AES began operating. The environmental risk posed by the Metsamor Nuclear Power Plant to the region was determined on the basis of a comprehensive analysis of the migration pathways of radionuclides in the atmospheric, hydrographic, and biological environments, as well as an integrated assessment of hydrochemical, biotic, and seismic indicators in the Aras River basin.

Keywords: *Metsamor Nuclear Power Plant (NPP), Nakhchivan Autonomous Republic, seismotectonic hazard, radioactive risk assessment, pollution, radionuclide contamination, environmental safety, river basin, energy.*

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Introduction. Energy production is one of the main factors in environmental pollution. However, the threat factor is not energy, but its form of production. Energy security protects the country, its citizens, society, state and economy. It is a state of protection from threats to reliable fuel and energy supply. These threats are determined by external (geopolitical, macroeconomic, cyclical) factors, as well as the management and activities of the country's energy sector [12]. There are several sources of radioactive pollution in the Aras River Basin. Among these, the Armenian Metsamor Nuclear Power Plant (MNPP), which has always been considered a source of danger for the region, should be noted (Figure 1). Although harmful effects such as alkaline environmental pollutants, greenhouse gases that affect global warming, heavy metals, waste, radiation and others arise during energy production, it is possible to benefit from all technologies provided that safety measures and clean production are ensured.

Energy safety must be taken into account in the MNPP inherited from the Soviet Union and having completed its operational life. Today, the Metsamor Nuclear Power Plant is one of the rare examples of nuclear reactors built without primary containment structures.

The main indicators of the MNPP are given in the table below, citing the World Nuclear Association [41].

As can be seen from the table, the two main reactors at Metsamor are of the VVER-440 type. VVER is a series of water-cooled, high-pressure water reactors designed in the late 1960s (Table 1). The two active reactors of this type (Kola-1 and Kola-2) are in Russia and have the same reactor type as Metsamor. As with Metsamor, these reactors have been refurbished to extend their life and increase energy production [39].

During the design of the NPP, it was decided to install a VVER-400 reactor instead of the RBMK reactor. This decision reflected the technological and engineering priorities of that period, however, subsequent assessments have raised concerns that safety considerations associated with the plant's design characteristics may be associated with elevated safety vulnerabilities under severe accident conditions. [39].

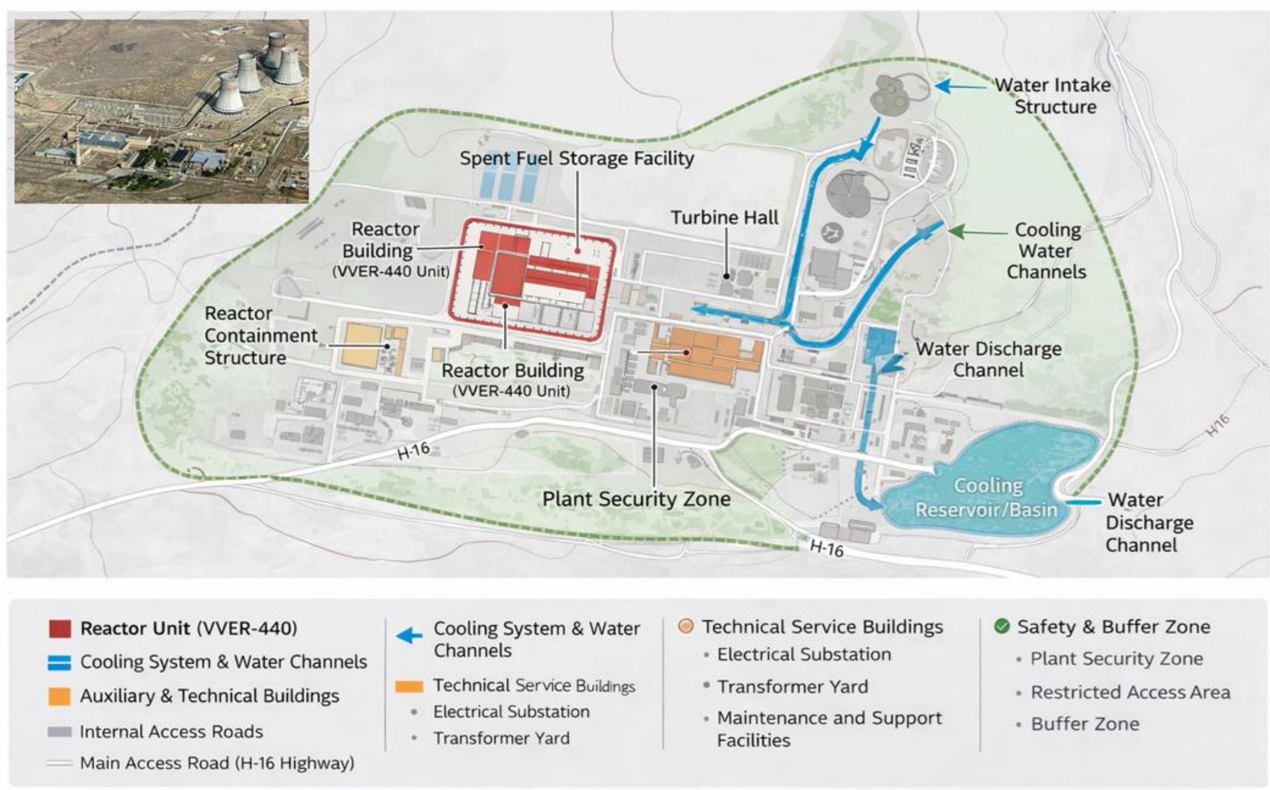

Fig. 1. Metsamor NPP (*Source:* Environmental Justice Atlas, based on OpenStreetMap data)

Table 1

Main indicators of Metsamor NPP

Reactor	Reactor type	Current situation	Amount of energy it provides, MW	Energy capacity, MW	Launch date	Term of service	Cleaning device
Metsamor 1	VVER 440/230	Not working	376	407.5	28.12.1976	25.02.1989	SBO-1
Metsamor 2	VVER 440/230	working	376	407.5	05.01.1980	(2016)	SBO-4

On October 15, 1982, at 09:58, a fire broke out in shaft 16 of the NPP. And at 12:45, control of the reactor was completely lost. Due to damage to the protection system, the cooling system failed, a dangerous accumulation of hydrogen was recorded, and the fire lasted for 7 hours. The fire was extinguished, but as a result, many people died, both workers and firefighters, and the survivors lost their lives within several months [15].

Although Russian state authorities and state-affiliated nuclear agencies later insisted on closing the plant, Armenia insisted on additional modifications to the plant's safety, such as improved fire doors. A UNDP energy expert noted that the Metsamor NPP's WVER reactor is old and lacks concrete containment domes to contain potential explosion debris [42].

The addition of a third and new reactor to the plant is a frequent topic on Armenia's agenda. One of the characteristics of the VVER-40 reactors is the lack of a protection system against the release of harmful waste into the atmosphere, and another is the weak fire protection system (IAEA-2022, Nuclear Technology Review. Report by the Director General [30].

The geographical location of the MNPP is shown in the table below (Table 2). As can be seen from the table, the South Caucasus and Eastern Anatolia is under greater danger, considering the possible accidents and the impact of atmospheric circulation in the region, even though the plant is located 74 km away from the Nakhchivan Autonomous Republic.

Station RDL (Releaseable Dose Limit) categories:

1) Category A – Metsamor;

2) Category B – Armavir, Margara, Ejmadzin, Igdir;

3) Category C – Yerevan, Tuzluca, Nakhchivan.

Regarding the distribution paths of radionuclides, they occur mainly from 3 sources - the Aras River, atmospheric circulation, and fish migration.

Table 2

Geographical location of Metsamor NPP

from Yerevan	40 km	In the West
From Igdir	16 km	In the North
From Gars	100 km	In the East
From Nakhchivan	160 km	In the northwest
It is located on the 8-point Alagöz-Aghri fault line in the Aras structural region		

106 medium and low-level accidents have occurred at Metsamor NPP, 78 of which were recorded through monitoring, 14 in the Türkiye and the Armenian Republic [25].

If we take into account that 38 years ago - in April 1986, a terrible accident occurred at the Chernobyl NPP in Ukraine, which was in a better technical condition than MNPP, the potential scale of nuclear risk becomes evident. The fire triggered by the accident was extinguished within nine days, during which large amounts of radioactive decay products were released into the atmosphere and subsequently deposited over vast areas of the former USSR and Western Europe. As a result of the radiation hazard, more than 300,000 residents were evacuated. Estimates of radiation-related fatalities range from approximately 4,000 according to United Nations assessments to up to 200,000 according to Greenpeace. Although Azerbaijan is geographically more distant from NPP, the country may face comparatively higher vulnerability in the case of an accident at Metsamor due to specific regional geographical, climatic, and atmospheric circulation features that could facilitate the transboundary transport of radionuclides.

The Chernobyl disaster in 1986, which falls into the same category, was the result of a flawed design of the Soviet reactor and serious errors by the plant operators. This was a direct result of the Cold War isolation and the resulting lack of any safety culture [40]. Moreover, the problem is not only the inadequacy of technology. Even with the use of the latest generation of technology, the city of Metsamor, Armavir Province, is constantly exposed to the risk of a sudden accident, being located on the fault zone of the Agri fault line [7]. This distinguishes it from other nuclear power plants in the world. The risks associated with the MNPP have received renewed international attention following the Fukushima Daiichi nuclear accident, which is widely regarded as one of the most significant nuclear disasters of the 21st century due to its long-term environmental and radiological consequences. Therefore, one of the primary concerns addressed in this study is the potential risk posed by the MNPP to neighbouring territories, particularly given that it is located approximately 120 km from the state border of Azerbaijan and 74 km from the border of the Nakhchivan Autonomous Republic. This risk is associated with the plant's ageing design, its seismic vulnerability, and the possibility of significant environmental impact in the event of a severe accident.

The aim of this study. The main goals are to investigate the impact of the potential hazard of the

MNPP on the surrounding areas, taking into account physical and geographical parameters to determine the direction of movement and scope of radionuclides with particular attention to the potential transport of contaminants to the territory of the Nakhchivan Autonomous Republic through air circulation and the Aras River, to conduct appropriate zoning, and prepare a map and scheme.

Literature Review

The assessment of radiological and environmental risks associated with NPPs, particularly those with aging infrastructure in seismically active regions, constitutes a critical and evolving field of research. This review synthesizes global perspectives on transboundary nuclear risk and situates the specific case of the MNPP within the broader context of environmental security in the South Caucasus.

In addition to this framing, practical case studies on VVER-440 units show that comprehensive seismic requalification coupled with targeted structural retrofits (e.g., bracing, roof stabilization, soil–structure interaction modeling) can materially increase safety margins under site-specific design spectra offering a relevant benchmark for Soviet-era designs like MNPP [10].

Global Context of Nuclear Risk and Transboundary Contamination

Major nuclear accidents have defined our understanding of transboundary radiological threats. The 1986 Chernobyl disaster demonstrated that radiological consequences do not respect political borders, with atmospheric dispersion depositing radionuclides across Europe [28]. Post-Chernobyl research established long-term contamination paradigms, showing how isotopes like Caesium-137 and Strontium-90 persist in ecosystems and bioaccumulate in food chains, necessitating decades-long environmental monitoring [33]. The 2011 Fukushima Daiichi accident reinforced the risk of natural hazards triggering technological disasters, highlighting vulnerabilities in plant design and emergency response [16]. These events underscore that risk assessment must integrate technological safety with geophysical and meteorological factors.

A key mechanistic insight from post-Fukushima research is the role of local atmospheric processes in contaminant transport. [35] demonstrated that radioactive plumes from Fukushima were frequently transported over 200 km to Tokyo via nocturnal local wind systems, including mesoscale low-pressure systems and sea breezes. This finding challenges the assumption that plume dispersion is governed solely by large-scale weather patterns. It highlights the critical importance of diurnal atmospheric cycles and local topography in determining contamination pathways for populated areas downwind of an NPP. Following this, [36] further showed that dispersion directions can be accurately predicted using near-surface wind patterns, providing a robust framework for modeling atmospheric pathways.

Parallel modeling for Türkiye and the South Caucasus using the FLEXPART Lagrangian particle model demonstrates that plume pathways and depositions vary sharply by season and synoptic regime; comparative scenarios for Akkuyu, Sinop and MNPP show south-dominant transport in summer months and north/east shifts in winter, with Chernobyl-like source terms producing an order-of-magnitude higher depositional load than routine scenarios [8].

A key contemporary focus is the specific vulnerability of aging Soviet-era reactor designs, such as the VVER-440/V-230 model operational at Metsamor. Technical assessments note that these Generation II reactors often lack modern containment structures and safety features, potentially elevating the consequences of a severe accident [34;16]. The International Atomic Energy Agency (IAEA) emphasizes that prolonged operation of such plants requires rigorous, ongoing safety upgrades and stress tests, a concern magnified for plants in high-risk zones [16].

Corroborating this, a detailed seismic requalification of VVER-440/213 units at Paks used 3-D finite-element models, soil–structure interaction (SASSI/STRUDYN), and staged retrofits executed during operation (e.g., new vertical bracing, roof diaphragms, frame-to-tower link bridges), and verified capacity to 0.25 g (H) / 0.23 g (V) site spectra–illustrating the feasibility and limits of retrofit-based risk reduction for legacy VVERs [10].

Seismic Risk as a Critical Multiplier for Metsamor NPP

The intersection of nuclear infrastructure and seismicity is a well-researched risk multiplier. Research shows that locating NPPs in active tectonic regions introduces a catastrophic risk dimension. This is acutely relevant for the MNPP, situated near the Anatolian fault system. [27] explicitly label Metsamor a "potential Caucasian Fukushima" due to its position in a high-magnitude seismic zone. Their analysis concludes that despite being designed for intensity 8 earthquakes, the plant is in a region with a potential for intensity 11 events.

The regional seismic hazard is exceptionally well-documented. [20] provide a comprehensive tectonophysical analysis of active faulting and associated natural hazards in Armenia, eastern Türkiye, and northwestern Iran. They identify the region encompassing the MNPP as a zone of concentrated, interrelated hazards where earthquakes interact with landslides and volcanic activity. The Ararat depression–a large pull-apart basin–is described as a high-risk area where major fault systems converge. The 1840 M7.4 Ararat earthquake, which triggered a volcanic eruption, massive landslides, and river course changes, serves as a historic analogue for the compound disaster potential in this transboundary region. [32] adds that while the plant is reportedly resistant to magnitude 7 seismic activity, international assessments reference a potential for magnitude 8 events. He also notes the plant lacks a primary containment structure standard in later VVER models, and international stress tests identified vulnerabilities in secondary safety features like fire suppression systems.

From a mitigation standpoint, evidence from VVER-440 retrofit programs indicates that segment-specific seismic demand (including soil nonlinearity and building rotation) can be addressed through targeted stiffness and load-path enhancements; however, such measures do not substitute for the absence of full-pressure containment, leaving residual consequence risk if severe core damage occurs [10].

Atmospheric and Hydrological Pathways of Radioactive Contamination

Transboundary pollution pathways are central to modeling regional risk from MNPP. Atmospheric circulation is a primary vector. Studies specific to the South Caucasus, such as those by [5;6], detail how prevailing wind patterns could transport radioactive plumes from Armenia into neighboring territories, including Azerbaijan's Nakhchivan Autonomous Republic, Türkiye, and Iran, within hours. The insights of [35] on nocturnal transport are directly relevant, suggesting that local wind systems (e.g., mountain-valley breezes in the Ararat basin) could dominate contaminant transport under calm conditions.

Applied dispersion experiments using FLEXPART for Akkuyu, Sinop and MNPP further show that identical source terms produce contrasting hot-spot geographies across months: August simulations favor southward export and North Africa/Eastern Mediterranean deposition, whereas December simulations shift maxima toward the Black Sea–Eastern Europe corridor–underscoring the need to parameterize diurnal cycles and seasonal synoptics in MNPP emergency planning [8].

Hydrological pathways, particularly river systems, facilitate another critical route for long-term contamination. Research on riverine transport shows that radionuclides can travel vast distances, affecting water quality, sediment, and biota far downstream [33]. [6] identify the Aras River as a key potential conduit for pollutants from the MNPP, impacting Nakhchivan and ultimately the Caspian Basin. [18] provide empirical baseline data from a transboundary perspective, conducting an environmental health risk assessment in Türkiye's Iğdır province, located ~20 km from the MNPP. Their study found that measured levels of background radioactivity and concentrations of selected pollutants in soil and drinking water were below permissible limits at the time, suggesting no imminent health risk. This study serves as a crucial baseline but also underscores the need for vigilance, highlighting the plant's risky condition.

Integrating these atmospheric and hydrological pathways with operational source-term brackets from scenario libraries (e.g., Chernobyl-analog vs. moderate releases) meaningfully alters predicted deposition fields by an order of magnitude, as shown in regional FLEXPART case work; therefore, monitoring thresholds and protective-action distances should be scenario-conditioned rather than static [10].

Bioaccumulation and Ecological Monitoring

The use of biotic indicators, especially fish, to monitor radionuclides and heavy metal pollution is a well-established methodological approach. Fish integrate exposure over time and space, making them effective bioindicators for chronic contamination. Studies demonstrate the significant accumulation of isotopes like Cs-137 and Cobalt-60 in various fish species. Recent research refines our understanding of factors influencing uptake. For instance, [36] provide specific data on short-lived radionuclides (^{54}Mn, ^{60}Co, ^{65}Zn) in fish. This biomonitoring is crucial for assessing human health risks from fisheries consumption, a major concern noted in global studies on contaminants in fish tissues.

Regional dispersion studies recommend aligning bioindicator sampling transects with season-dependent plume corridors (summer southward vs. winter northward pathways) to maximize detection probability and improve source attribution in the Aras–Kura basin [8].

The Regional Research Gap and This Study's Contribution

While the global literature provides a robust framework, a discernible gap exists in integrated, spatially explicit risk assessments for the MNPP that focus concretely on downstream and downwind regions like Nakhchivan. Much existing work addresses specific vulnerabilities–such as atmospheric pathways, general threat levels, or seismic geology–in isolation. For example, while [27] provides a strong geological risk argument, they do not model detailed contamination pathways. [33] offers a comprehensive overview of operational challenges but does not provide a spatially explicit risk model. Studies like [18] offers valuable baseline data for one neighboring region but do not model the integrated, multi-vector risk across the entire Aras Basin. Furthermore, the critical insights on local-scale plume transport mechanisms from [35] have not been systematically applied to model potential atmospheric exposure pathways for Nakhchivan from the MNPP.

Few studies combine empirical hydrochemical analysis, biological monitoring, detailed seismic zonation, and high-resolution atmospheric modeling that accounts for diurnal cycles into a holistic, spatially differentiated ecological risk zoning map for the entire Aras River basin. This study aims to address this gap. It develops a composite spatial model of transboundary risk by integrating these multi-hazard perspectives. It thereby contributes a needed regional case study to the broader discourse on the environmental safety of aging nuclear infrastructure in conflict-prone, seismically active zones characterized by compound natural hazards.

Accordingly, the present work couples (i) segment-aware seismic forcing and retrofit limits for legacy VVERs, drawing on demonstrated requalification practices, with (ii) FLEXPART-based seasonal dispersion ensembles for MNPP and comparators (Akkuyu, Sinop), to produce scenario-conditioned exposure maps and monitoring priorities for the Aras basin.

Materials and research methods. ***The role of seismic and tectonic factors in shaping the environmental risk of the study area.*** The MNPP is located in an 8-point earthquake zone and on the East Anatolian fault line. After the Spitak earthquake in 1989, the MNPP, which provided 30-35% of Armenia's electricity, was shut down, and in 1993 it resumed operations with 2 units [44]. Taking into account all these dangers, we have prepared a map of the seismological zones of the Republic of Armenia based on the analysis of tectonic movements that have occurred in the areas near the station since 1980 and the results of these movements. Within the scope of the study, earthquake data covering the period 1980–2025 were obtained from the United States Geological Survey (USGS) Earthquake Catalog. The dataset was subsequently processed using appropriate geoprocessing tools in ArcMap software, resulting in the preparation of a tectonic activity–based zonation map of the study area. (Figure 2).

As can be clearly seen from the map, earthquakes with a magnitude of 4.5 and above have occurred almost every year. Considering that the NPP

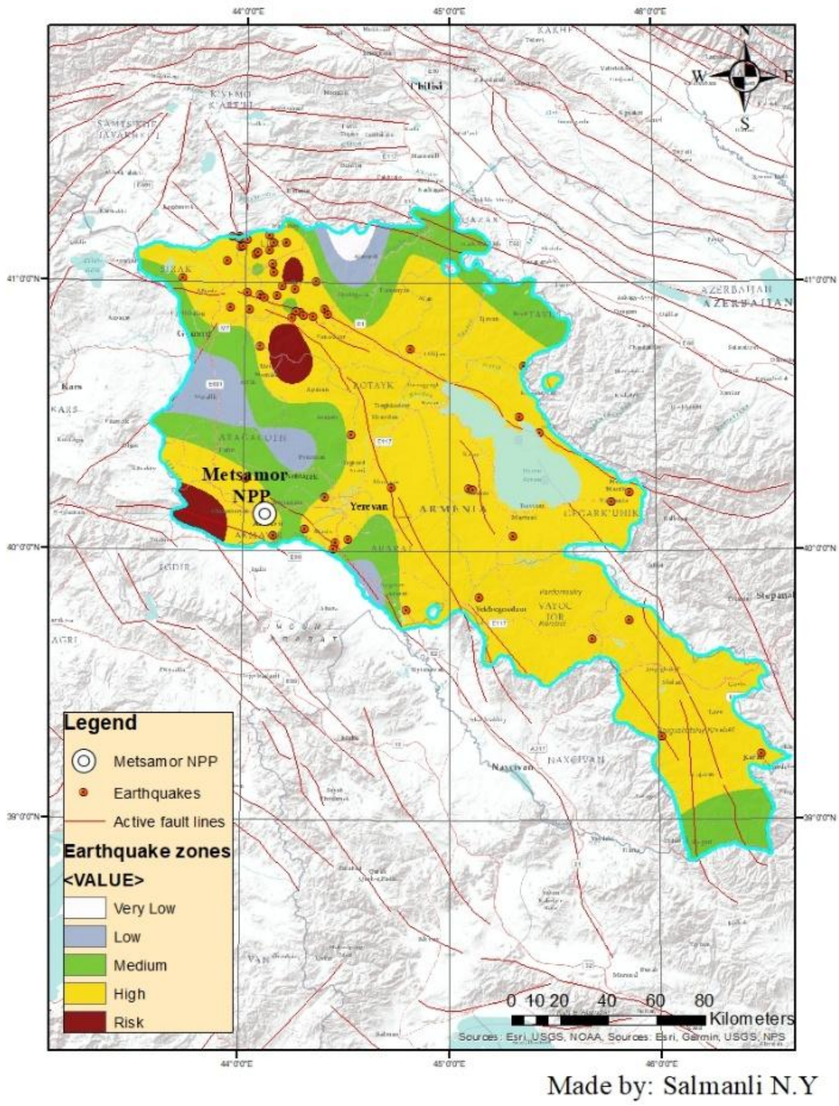

Fig. 2. Seismological zones of the Republic of Armenia

is in an emergency state and has reached the end of its operational life, we can see how dangerous this is for the region. Moreover, the problem is not only related to the inadequacy of technology. Even if the latest generation technologies are used, the location of the city of Oktyabryan on the Aghri fault line poses the risk of a sudden accident at any time. Under normal conditions, according to international standards (ISO 4917-1:2024 – Design of nuclear power plants against seismic events; IAEA Safety Standards Series No. SSG-67 – Seismic Design for Nuclear Installations (2021)) nuclear facilities should not be operated in conditions where there is an unaccounted for or unacceptable level of seismic risk without appropriate design measures. In 2006, the closure of that station was deemed necessary by the decision of the European Union, but despite this, it is still in operation.

The role of atmospheric circulation in the spread of radioactive waste in the Middle Aras natural region. The transboundary impact of the MNPP to the region, as well as to the Republic of Azerbaijan, is mainly atmospheric circulation [26] and, to some extent, pollution through the Aras River. In this regard, when studying the environmental impact of the MNPP, it is important to characterize the natural climatic conditions of the area where the plant is located.

Climate plays an exceptional role in the spread of radioactive substances. Many factors that shape climatic conditions - altitudinal zonation, geographical location, orographic features and the complexity of the relief - also determine the ecogeographical characteristics of the territory [2]. A number of synoptic-scale air masses influencing the territory of Azerbaijan, primarily mid-latitude westerly and south-westerly continental air flows, traverse the area of the MNPP and subsequently enter the Nakhchivan Autonomous Republic. [5].

Therefore, in the event of an accident at the station, the part of the Azerbaijan territory is under more serious danger than the Republic of Armenia. The interaction between climatic processes and environmental hazards has been widely discussed, particularlyregarding pollutant dispersion mechanisms and their potential impact on regional development [29]. Thus, during the accident at the Chernobyl NPP in 1986, thousands of people were evacuated from nearby settlements or continue to live in the affected areas of Belarus, Russia and Ukraine.

Although some studies have been ongoing for many years to provide a better understanding of the situation regarding the MNPP, they are not enough to determine the risk [22]. Taking all this into account, the atmospheric circulation of the region was studied through the Earth Nullschool website.

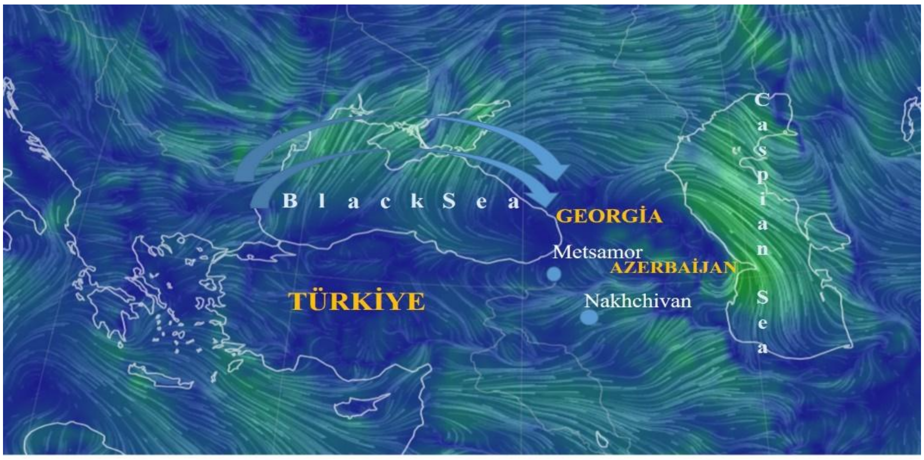

Fig. 3 A. Continental maritime air masses

The entry of radionuclides released from the NPP into the area through air currents as a result of any accident that may occur has been analyzed using data obtained from Earth NULL School. As shown (Figure 3 A), continental marine air masses enter the area over the MNPP, and the southern cyclones that dominate throughout the year (Figure 3 B) also enter the area over the NPP after which they continue to move in the direction of Azerbaijan, which once again proves how great a threat the Nakhchivan Autonomous Republic faces.

Under neutral (isothermal) atmospheric stratification and wind speeds of 5–10 m/s, the time it takes for the radioactive cloud to reach the territory of the autonomous republic may be 2 hours. At this time, the number of people who may be exposed to ionizing radiation in the contamination zone, which is 270 km long, 13 km wide, and has an area of 2980 km^2, is predicted to be 440 thousand people [3].

In order to timely warn the population in case of accidents and other radiation hazards that may pose a potential risk, as well as to eliminate the consequences, modern radiation search and measurement devices made in the USA and Germany, new personal protective equipment protecting the respiratory organs and body surface, as well as degassing equipment

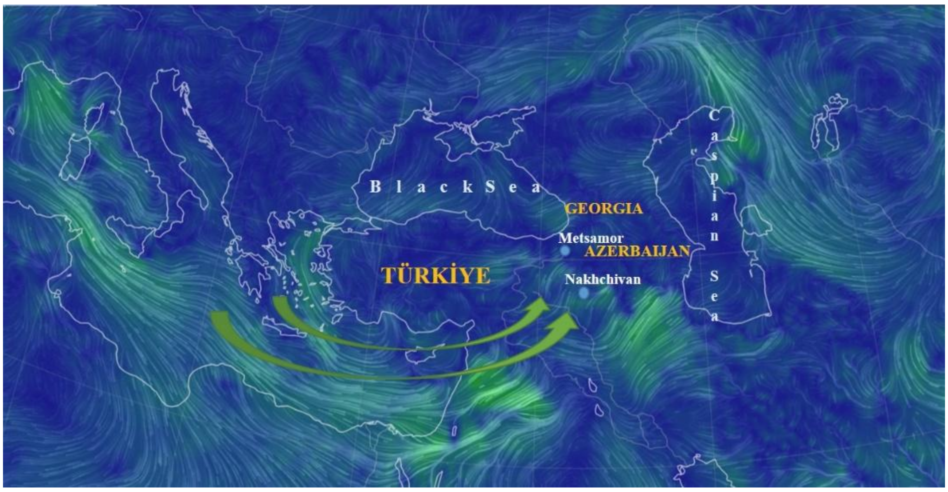

Fig. 3 B. Southern cyclones

have been purchased. This equipment is stored in the material and technical base of the Nakhchivan Autonomous Republic Ministry of Emergency Situations and is ready for use if necessary [3].

Studying the migration of radioactive substances in water bodies and the role of fish in this process. At the next stage of the research work, the dynamics of radionuclides in water bodies, the conservation of harmful substances and the role of fish in the migration of radioactive substances in water bodies were studied [1]. Surface waters are the second most important means of spreading radionuclides after atmospheric processes.

There are several sources of radioactive danger in the Aras River drainage basin. In addition to the MNPP, these include the Kacharan Ore Refinery (KOR) and the Radioactive Hazard Junction (RHJ) located in the Gayan Plain. Since the object of our study is the impact of the Metsamor NPP on the environment, we will not dwell on the others.

As a result of during the last eight years of research, it was observed that the level of radioactive substances in the Aras River exceeded the norm by 32 times [14]. Wastewater generated at the NPP may contain both trace levels of radionuclides and chemical contaminants, primarily detergents used in equipment decontamination and cleaning processes. The chemical composition of these effluents includes anionic surfactants, sodium hexametaphosphate, and related compounds. The main composition of detergents observed in the river water is anionic activated detergents, sodium hexametophosphate soap and others. Pollution of the atmospheric air, as well as the Aras River, also occurs through leakage from treatment systems, as a result of violation of the rules for storing radioactive waste, from the ventilation facilities of the MNPP, during waste deactivation and fuel regeneration. It should be noted that even if safety standards are fully observed at the NPP, the radius of influence of radionuclides through diffusion reaches up to 200 km. The radiation dose of the population living in the indicated area can vary from 0.1 to 60% [19].

Observations conducted since 1995 at the "Aras Water Junction" reservoir show that radioactive contamination material released directly and indirectly into the Aras River from the Armenian MNPP, especially the water used in the water cooling system, has a significant impact on many living creatures living there, especially fish, in addition to the river water.

The Aras reservoir is home to 26 species of fish and 17 species of crustaceans. According to the information received from the National Fish and Aquatic Resources Service the measured levels of radionuclides (Cs-137, Sr-90) in samples taken from ichthyofauna exceed the established norm for freshwater organisms (130-100 Bq-kg) [17]. Fish are contaminated with radioactive elements in various ways. These fish feed as a result of direct adsorption of radioactive substances accumulated in their bodies, as well as through water filtered through gills. Radioactive elements usually enter the internal organs through the skin, gills, and oral system. One of the main sources of contamination of fish with radioactive elements is through the food chain. Young fish and some older fish feed on plankton, and the amount of radionuclides in these plankton is 100 and even 1000 times higher than in the surrounding waters. Therefore, we believe that the main sources of contamination of fish are aquatic plants. Planktophages rapidly absorb pollutants from water. ^{54}Mn and ^{65}Zn are more efficiently transported in this way due to their biological functions in metabolic processes [21].

These elements accumulate in the shells and bones, while 60 Co is less common in this group because it does not bind strongly to plankton [30]. Radioactive substances entering internal organs and cells can also play the role of a source of secondary contamination.

Radionuclides, like other nuclides, enter the body through the alimentary system. The composition of natural radionuclides and ^{137}C has been studied by gamma-spectrometry. The activity concentration of ^{40}K is measured in the range of 44-165 Bq kg-1 [9]. Their accumulation in the body and their effect on the body depend on the type of food products and the state of the substance. While some nutrients are easier to regulate by the body, they are also easier to distribute in the body. Thus, radioactive substances in solid food are often not fully absorbed. In contrast, nutrients in ionic form are more easily absorbed by organisms. Fish are freed from radioactive elements in several ways: general body flushing, elimination of metabolic products from the body, and the decay and neutralization of radioisotopes.

Radiological effects are more clearly observed in some living organisms living in water bodies and are considered the main indicator [33]. The accumulation of radioactive substances in the body and cells of fish, as well as their distribution and excretion from the body, depends on many conditions. One of these conditions is the chemical properties of radioisotopes and their half-life, the type, age, physiological state and ecological conditions of the fish living in the water. The accumulation of radioisotopes in the body and cells of fish also depends on the concentration of radioisotopes in water and their time and period. Thus, this accumulation depends on changes in the water level at different times of the day and in different seasons and in the river.

Results. In the research work, the analysis of samples taken from the water of the Aras River and the corresponding analysis of fish as an ecological factor were used to determine the dynamics of radioactive waste released by the plant into the environment because this transboundary river basin creates shared geographic and hydrological pathways of environmental risk for regions along its course. Based on the results obtained, three ecological regions were identified and they were characterized separately. Pollution of the river basin with radioactive substances is a source of danger not only for the region, but also for the entire Caspian basin.

Also, an analysis of the tectonic processes that have occurred since 1980, including data on the strength, epicenter, and fault lines of earthquakes from the USGS website, was conducted in the region where the nuclear power plant, which was built to withstand a magnitude 7 earthquake, is located in a 8-magnitude tectonic zone, and is in an emergency state, and a seismic zoning map of the Republic of Armenia was prepared.Considering the structure and natural characteristics of the Aras river basin within the Nakhchivan Autonomous Republic, and the possibility of radioactive waste spread, it is possible to divide the territory of the basin into 3 different parts. Taking this into account, environmental vulnerability zoning of the Aras River basin has been prepared below (Figure 4).

The first part covers the upper reaches of rivers up to 2000-2200 m of absolute altitude. In this area, rivers are formed from small tributaries, springs, and snow waters, and flow in steep-sided valleys in the alpine and subalpine meadow zone. The waters are ecologically clean. No radioactive waste is found in this section (Table 3).

In the second part, rivers enter the middle mountainous zone, flowing rapidly through narrow and deep valleys, forming numerous rapids and waterfalls sometimes reaching a height of 20-30 m. This section covers areas of river basins at an altitude of 2200-2000 m and 1000 m. This section is subject to weak and very weak erosion. Traces of pollution are found after the flow of western winds (Table 3).

The third part includes the plain along Aras River located below 1000 m within the Nakhchivan Autonomous Republic. In this section, as the rivers enter the plain, their speed decreases significantly, their flows calm down, their beds expand and gradually merge with the surrounding relief. During the dry season of the year, due to arid climatic conditions and intensive use in agriculture, their tributaries often do not reach the Aras. Pollution is moderate. On the map, we have included the section from Sadarak to the Aras reservoir within the Nakhchivan Autonomous Republic as an ecologically stressed zone. This is due to the pollution of tributaries received from the territory of the Republic of Armenia by industrial and domestic sources, including radionuclides from the MNPP (Table 3).

The Aras reservoir plays a filtering role in the area. It is clear from the samples taken at the entrance and exit of the river into the reservoir that the amount of pollutants (phenols, heavy metals, nitrogen-phosphorus salts, etc.) in the water is different.

Floods in rivers occur mainly in the spring, as a result of snowmelt and heavy spring rains. Radioactive substances are rarely found during this period. The intensity of snowmelt, the absolute height of the feeding area, its shape and size have a serious impact on spring floods, as well as the degree of pollution [4].

Flash floods occur mainly in active river valleys and have great speed and destructive power. Water separates the sedimentary materials it brings mixed with it into components according to their volume, weight, and type and spreads them throughout the delivery cone. Flash floods are more widespread in the region and occur almost every year. However, structural floods that occur periodically cause greater destruction. Floods have a significant impact on the mechanical composition of the

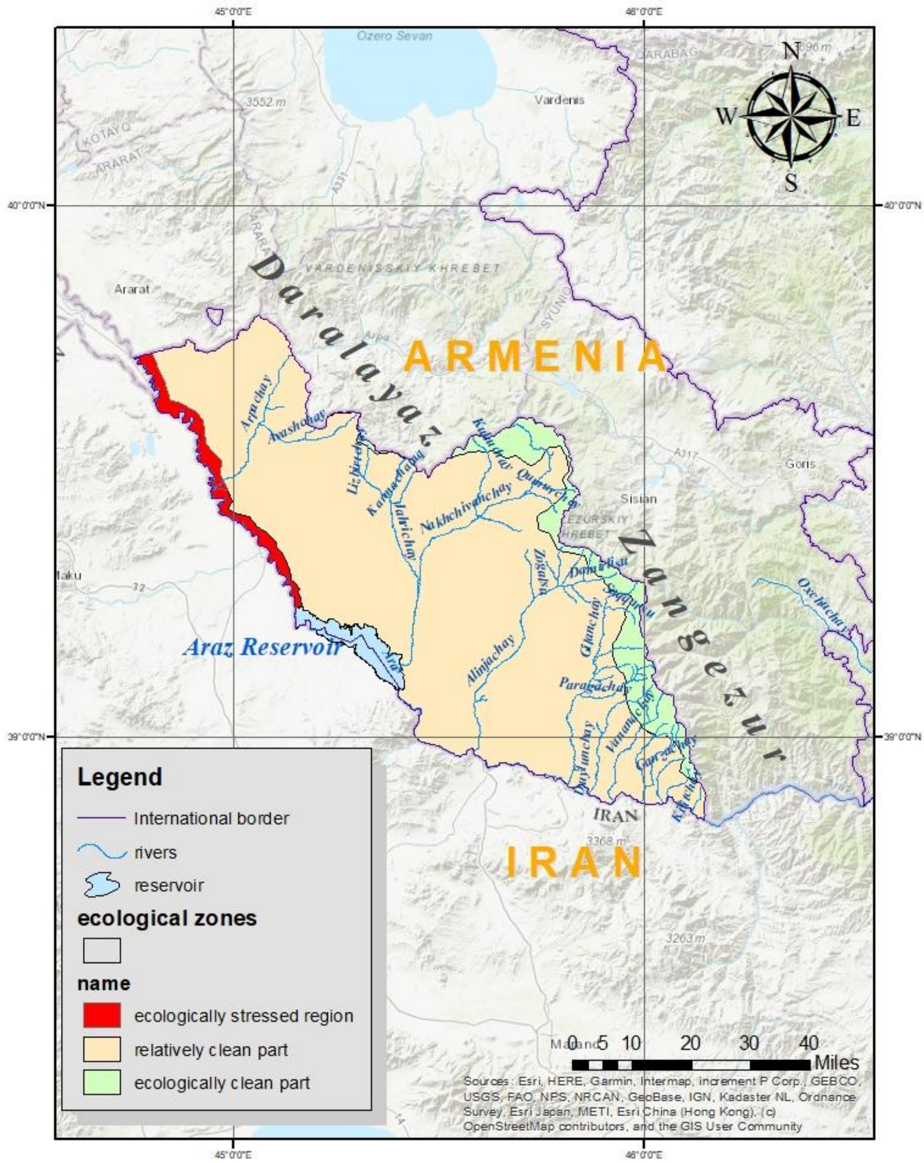

Fig. 4. Environmental vulnerability zoning map of the Aras River basin
in Nakhchivan Autonomous Republic

Table 3

Environmental vulnerability zoning of the Aras River system according to the degree of pollution

Zones of the river system according to the degree of pollution
Ecologically clean part
This includes the streams and river tributaries that enter the upper part of the Zangezur and Daralayaz mountains.
Relatively clean part
This includes the flow of the Aras River from the reservoir to the Okchuchay and its tributaries entering from the Zangezur (Alangez) mountain range.
Ecologically stressed region
The section from the confluence of the Aras River with the Arpachay River to the upper part of the "Aras Water Junction" reservoir. The main sources of pollution in the region are radionuclides from the Metsamor NPP and industrial and domestic waste entering through the Zangi (Razdan) River.

water of the Aras River [21]. The composition of waste entering the Aras River varies depending on the characteristics of the polluting source and changes in water volume, and manifests itself in three forms - dissolved, undissolved, and colloidal.

Wastes discharged into the Aras River system are divided into three groups according to their origin: mineral, organic and bacterial. Mineral-origin pollutant concentrates consisting of various salts, suspended mechanical substances, and rock particles enter the water both naturally and anthropogenically [23]. The main components of organic waste are hydrocarbons, as well as carbon dioxide, nitrogen, phosphorus, potassium, sulfur, chlorine, etc. compounds. The bacteriological composition of the river is characterized by the presence of pathogenic and indicator bacteria in the water. In the water samples we took from the Aras River, EL-tor vibrios, which pose a special threat, were found twice, and Heiberg infection was found once. Mineral fertilizers and toxic chemical compounds, which are considered diffuse pollutants observed in the Aras River.

As a result of studies, it has been observed that the amount of radioactive substances and radionuclides entering the Aras River and the reservoir with the cooling water discharged from the MNPP, which is considered more dangerous from an ecological point of view, has recently decreased below the norm and sometimes completely disappeared. It should be noted that 12-163 tons of polluted water is discharged from the NPP into the river per day [24].

All harmful wastes affect the organic, sanitary, toxic, etc. qualities of the river water, changing its many physical properties, color and transparency. In parallel with this, the amount of dissolved oxygen in the water changes, eutrophic processes intensify, the hydrochemical and hydrobiological regime of the water is disturbed, and its quality decreases[11]. The increase in bioproductivity disrupts the general balance of the ecosystem in the water and its restoration cannot occur for many years.

Analysis of water samples taken from various parts of the Aras River, its tributaries and the reservoir shows that the ecological tension reaches its maximum in August-September, when the water level drops to a minimum [6].

During these periods, it has been recorded that the levels of some substances in the water, such as phenol, ammonia, nitrates, and nitrogen, are 500 times higher than normal. On the other hand, as a result of the sharp drop in water level, thermal circulation in the water is disrupted, and the specific gravity of pollutants increases due to the decrease in volume and water consumption, as a result, the water heats up rapidly and favorable conditions are created for the development of parasites in some fish species.

The percentage of pollutant concentrations decreases sharply during the months of March-May, when the levels are at their maximum (Table 4) [14].

Below is an analysis of water samples taken from different locations for comparison.

The “Aras Water Junction” reservoir can be divided into the following 4 regions according to its ecological status.

Table 4

Analysis of water samples taken from different locations

Water composition and temperature	The limit of the norm	Arpachay	Aras (Near Sadarak)	Aras Canal	Water Reservoir (Platina)	Reservoir (upper part)
Water temperature, C^0	-	13.1	13.4	16	22.4	23
PN	6.8-8.5	8	7	8	9.2	9.1
Transparency (sm)	30	25	25	23	18	19
Chloride (mg/l)	300-350	35.445	70.89	63.16	90.38	170.14
Sulfate (mg/l)	100-500	-	-	462	147.72	686.88
Acidity-alkalinity (mg/l)	-	109.84	103.71	118.98	91.53	175.99
Calcium (mg/l)	180	200.4	160.32	168.09	59.09	152.30
Magnesium (mg/l)	90	121.6	48.64	36.44	58.97	84.51
Potassium (mg/eq/l)	7.00	20	12	11.1	7.3	14.55
Nitrite (mg/l)	0.08	0.001	0.004	0.004	0.02	0.04
Nitrate (mg/l)	9.1	1.0	1.0	0.5	1.0	1.2
Ammonium (mg/l)	0.05	0.08	0.04	0.08	2.0	8.00
Dry residue (mg/l)	1000	0.888	0.038	1223.5	472.5	1610
Suspended matter (mg/l)	0.75	0.09	0.01	23.85	28.3	227.45
Radioactive contamination	0.1-1.0	-	1.4	-	-	-

Platina-dam region. The physicochemical indicators of the water in the part of the reservoir near the dam, its color, transparency, amount of suspended matter and water circulation differ from other areas. This zone is considered ecologically clean and radioactive elements are almost not found in the water or are found only in the internal organs of fish migrating here, which is below the norm. There is no long-term accumulation of radioactive elements in the skin of fish.

Transition region. Pollution in this region is seasonal, the level of radioactive and heavy metals reaches a maximum in the summer months. During periods of abundant water, when the level is high, the amount of radioactive elements is the lowest. This usually coincides with periods of abundant precipitation, as well as active snow melting. Although the total amount of radioactive elements in water is high, it is low in terms of their amount per unit volume.

Delta region. The physicochemical properties of the waters are identical to the properties of river waters. Unlike the dam region, radioactive elements can be found in the skin of some fish, and bottom-dwelling fish are not found in the dam region. The region is shrinking due to river discharges, and in turn, its area is increasing due to the transition region. Due to river discharges, the reservoir has shortened by 19 km in the delta region. Radioactive waste is found in the alluvial sediments collected here, as in the water body. These wastes enter the Aras River, and from there to the delta region with the waters of the cooling system discharged from the NPP. Radioactive waste collected in the sediments decomposes and neutralizes over time.

Coastal region. The accumulation of harmful substances in this region is mainly seasonal. During the mezhe period of the river and in the hot summer months when the reservoir water is used for irrigation, radioactive and heavy metal pollution reaches its maximum. Radioactive elements are found in the sediments in the delta region, and their amount and accumulation are out of general regularity. Thus, the accumulation of radioactive elements in river water depends on its direction in the reservoir, the amount of water entering the reservoir, the temperature of the water, and others.

Radioactive elements in sediments are found in the delta region, and their amount and accumulation are not consistent with general laws. Thus, the accumulation of radioactive elements varies depending on the direction of the river water in the reservoir, the amount of water entering the reservoir, the water temperature, and in fish, along with these conditions, the direction of their migration. Also, as mentioned above, the amount and time of waste discharged from the NPP into the river affect the composition of the collected materials. Toxic compounds released into the aquatic environment from natural and anthropogenic sources are absorbed by aquatic organisms. Even low levels of toxic metals can threaten the health of aquatic organisms and humans [13]. When studying radioactive substances in fish, it is necessary to approach this issue from two directions. The first is the effect of fish as carriers of radioactive substances that have entered their bodies, and the second approach is the study of the impact of radioactive substances released from their bodies on the environment and their study. It should be noted that the contamination of fish in the basin with radionuclides and heavy metals is a source of danger not only for the Nakhchivan autonomous republic, but also for all the living creatures of the Caspian water area and the basin states [5]. In our opinion, the solution of the second problem is more relevant. As noted, radioactive elements enter their internal organisms through the skin, gills and mouth. Young fish accumulate more radioisotopes in their bodies than older fish. In addition to the above factors, the accumulation of radionuclides is also affected by the season and periods of the year. According to ecologist N.I. Bulyamov (1983), the accumulation of radionuclides in the body also depends on the mineralization of water and its chemical composition. Of course, the effect of water temperature is great here. This is proven by the samples we took from the same test point in the reservoir at different times. In our opinion, much depends on the type of fish and its physiological activity. Thus, fish that lead an active life can accumulate more radioactive elements. When active fish move from the dam area, which we consider ecologically clean, to other areas of the reservoir, the process of accumulation of elements is activated in them. Analysis of samples taken from catfish (Silurus glanis) that have an underwater lifestyle during the cold period in the transition region in different years shows that radionuclides are almost absent in this type of fish that lead a bottom life. In the delta region, the most radioactive isotopes accumulate in bottom-dwelling fish.

Radioactive elements entering the water first accumulate in invertebrates, aquatic invertebrates and aquatic plants, which are the main food of fish. The decrease in radioactive elements in them also affects fish. Considering the ratio of the mass of water in the food to the total mass, the most radioactive isotopes accumulate in aquatic plants. This is also due to the lack of solid waste, that is, solid substances, in plants during the vegetation period.

Conclusion. As a result, the MNPP is a serious source of danger for the region, as it is located on a 8-magnitude earthquake zone and the Anatolian fault line and has reached the end of its operational life. The waste released into the atmosphere by the plant and spread through the water cooling system, taking into account the movement of air masses and relief features, may cause the formation of radioactive contamination zones in the territory of the Nakhchivan Autonomous Republic.

Since the air masses entering the Nakhchivan Autonomous Republic pass over the Metsamor Nuclear Power Plant at different times of the year or regularly, any minor accident or radioactive leakage will cause isotherm (vertical stability of the air) and wind speed to cause contamination of ecosystems with radionuclides. In this case, the radiation dose rate is expected to be in the range of 0.001 R/hour-0.007R/hour, which is 700 times higher than the daily radiation background.

Analysis of water samples taken from different points shows that many physical, chemical and biological indicators in the water in the area exceed the established norms, and these indicators vary depending on the water level in the seasons. This is proven by the samples we took from the same testing point in the reservoir at different times.

Taking into account the structure and natural characteristics of the basins, the impact of radioactive waste, it is more correct to divide the Aras River basin into three different parts (ecologically clean part, relatively clean part, ecologically stressed region) in the Nakhchivan Autonomous Republic.

The accumulation of radioactive substances in ichthyofauna has been studied in two directions. The first of these is as a carrier of radioactive substances that have entered the organisms of fish, and the second approach is the study of the impact of radioactive substances released from their bodies on the environment and their impact. The solution of this problem is more relevant.

The results of research conducted in different years show that the greatest accumulation of elements is in the catfish (Silurus glanis) and perch (Perca fluviatilis L.) fish.

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Метою дослідження є вивчення процесів атмосферного розсіювання, а також оцінка впливу радіоактивних скидів на навколишнє середовище у зв'язку з розташуванням реакторів МНПП у прикордонному регіоні з високим сейсмічним ризиком та дослідження можливого перенесення забруднюючих речовин до Нахчиванської Автономної Республіки повітряними потоками та річкою Аракс. Дослідження охоплює просторовий аналіз транскордонних радіоекологічних небезпек у басейні річки Аракс, заснований на зборі гідроекологічних зразків у польових умовах, лабораторному аналізі води та іхтіофауни, геоінформаційному картографуванні та комплексній оцінці сейсмотектонічних ризиків. У зразках води досліджувалися фізико-хімічні, мікробіологічні та біологічні параметри (pH, важкі метали, нітрати, фосфати, вміст кисню тощо), а рибу використовували як біоіндикатори для оцінки довгострокового накопичення радіонуклідів. Крім того, за допомогою програмного забезпечення ArcGIS (ArcMap) вивчали фактори ризику тектонічних процесів, що відбувалися та можуть відбуватися в цьому районі, та підготували карту екологічного зонування частини басейну річки Аракс. Вперше в Нахчиванській Автономній Республіці оцінено радіологічний ризик, пов'язаний з Мецаморською АЕС, на основі комплексного регіонального аналізу атмосферного переносу, річкового розсіювання та біологічної міграції радіоізотопів. В останні роки було проведено екологічне зонування та підготовлено карту, що ілюструє вплив АЕС Мецамор на басейн річки Аракс та водосховище Аракс. Новизна дослідження полягає в розробці просторової моделі транскордонного екологічного ризику в басейні річки Аракс, що базується на інтеграції гідрохімічних показників, даних біотичного накопичення та аналізу сейсмічної небезпеки. Дослідження визначило, що основними шляхами розсіювання радіонуклідів є річка Аракс, атмосферна циркуляція та міграція риб. Беручи до уваги потенційне розсіювання радіоактивних відходів у басейні, річки району були розділені на три категорії за їх екологічним станом: чисті, відносно чисті та сильно забруднені. Карта, складена за допомогою ArcMap, підтверджує сейсмічний ризик району, показуючи, що за останні 45 років з початку роботи АЕС було зареєстровано сотні землетрусів з максимальною магнітудою 7. Екологічний ризик, який становить Мецаморська атомна електростанція для регіону, було визначено на основі комплексного аналізу шляхів міграції радіонуклідів в атмосферному, гідрографічному та біологічному середовищах, а також комплексної оцінки гідрохімічних, біотичних та сейсмічних показників у басейні річки Аракс.

Ключові слова: *Атомна електростанція (АЕС), Мецамор, радіоактивні витоки, радіологічне забруднення, атмосферна циркуляція, сейсмотектонічний ризик, радіонукліди, Нахчиванська Автономна Республіка, річка Араз, екологічне зонування.*

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