

Aquatic Ecosystem Degradation Due to Industrial Pollution: A Case Study of the Okchu River

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ABSTRACT

State of the problem. Once recognized for its substantial hydropower potential of about 130 million kWh annually, the Okchu River is now classified among the most polluted rivers globally due to severe heavy metal contamination, making it unsuitable for human use without extensive treatment. The ecological degradation, mainly caused by copper-molybdenum mining in Armenia's Gafan and Gajaran regions, has led to declining biodiversity, unsafe water quality, and health risks for communities dependent on the river.

Object learning. The article proposes a comprehensive strategy for developing hydropower resources along the Okchu River in Azerbaijan while simultaneously addressing ecological challenges. It aims to restore the river's health by combining hydropower development with corrective ecological measures, ensuring a balance between energy production and environmental sustainability.

Methodology. The research employs historical and contemporary datasets, including water and sediment quality assessments, supported by environmental monitoring conducted by Azerbaijani and international bodies. Analytical approaches are used to measure concentrations of heavy metals – specifically copper, iron, and nickel – and to assess their ecological consequences on the river's ecosystem and groundwater resources. In 2023, 108 water samples and 39 bottom sediment samples from the Oxchuchay River underwent 1,728 physico-chemical, 398 physico-chemical, and 3 ecotoxicological analyses. Findings revealed that iron, zinc, copper, and manganese concentrations were considerably higher than those of other metals.

Research results. Findings reveal that copper-molybdenum concentrations far exceed permissible limits, endangering drinking water safety, agricultural irrigation, and aquatic life. Monitoring at the Shayifli station in 2023 revealed frequent exceedances of ammonium (up to 2.4 mg/L, 4.8× MPC) and manganese (up to 674 µg/L, 6.74× MPC), indicating episodic contamination. Iron levels fluctuated widely, peaking at 946 µg/L (3× MPC) in May and dropping to 37.7 µg/L in October. Hardness and sulfate remained mostly within limits but showed clear seasonal trends, linked to climatic and hydrological factors. The study highlights the declining ecological condition of the Okchu River while presenting a hydropower development plan expected to generate 120–140 million kWh annually, supplemented by an additional 70 million kWh from a new Hydropower Plant. To safeguard ecological flow, a 5.3 km purified-water pipeline to the Shayifli reservoir is proposed, along with innovative water management techniques and advanced monitoring systems.

The scientific novelty of the research. This study introduces an integrated framework that prioritizes sustainable hydropower generation alongside ecological restoration. By combining cross-border collaboration, advanced monitoring technologies, and ecological flow management, it outlines a model for balancing industrial development with the urgent need for environmental protection in transboundary river systems.

Keywords: *chemical parameters of water, ecosystem, hydropower, water resources, heavy metal pollution, monitoring of rivers, treatment methods, ecological assessment, water quality monitoring.*

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Introduction

The Okchu River, which originates from Kapicik Mountain (3,285 meters) in the Zangezur range, enters Azerbaijan at an elevation of 630 meters. After flowing approximately 30 kilometers, it reaches the Araz River at an elevation of 300 meters. Nearby urban centers, such as Gafan and Gajaran in Armenia, as well as Zangilan and Minjivan in Azerbaijan, are situated along its banks. While the river holds an annual hydropower potential of 130 million kWh, it has been subjected to extensive pol-

lution for years due to industrial discharge from the copper-molybdenum mines adjacent to Gafan and Gajaran. The pollution levels have surpassed all environmental standards, leading to the devastation of the river's ecosystem. The Okchu River is now categorized as one of the most polluted waterways globally, resulting in significant health hazards for those utilizing its water for various purposes.

Recent reports from both Azerbaijani and Armenian media indicate that Armenia continues to release industrial wastewater into the Okchu River

without adequate treatment. A report by the Ministry of Ecology and Natural Resources of Azerbaijan noted that the levels of copper-molybdenum compounds in the river water were twice the acceptable limit, with iron levels four times higher and nickel levels seven times higher. Water samples from the Okchu River revealed alarming environmental risks, with water often displaying a white or yellowish hue. Studies conducted by experts from the Siberian Branch of the Russian Academy of Sciences in 2017 indicated that the water quality of the Okchu River corresponded to the IV degree of ecological condition typical of mining-impacted water basins [3]. The influx of river water contaminated with heavy metals represents a significant ecological catastrophe. Moreover, the Okchu River serves as a primary source for groundwater recharge in the Zangilan region, which is increasingly threatened by the accumulation of heavy metals along the river channel and their eventual mixing with groundwater. Immediate action is necessary to safeguard the river's ecosystem and the precious groundwater resources it supports [2].

Materials and Methods

The Okchu River's hydrological dynamics were analyzed by collecting water samples from various locations along its course, particularly in areas impacted by industrial activities and cross-border pollution from Armenia. Monthly sampling was conducted from January 2021 (still continued) to assess seasonal variations and contamination levels.

Samples were analyzed for heavy metals (copper, molybdenum, manganese, iron, nickel, cadmium) using standard analytical techniques. Measurements of dissolved oxygen, biochemical oxygen demand (BOD₅), and nutrient levels (ammonium, nitrite) were also performed. In addition, sediment samples were collected to evaluate the accumulation

of heavy metals and their persistence. Long-term hydrological data from the Okchu River were statistically analyzed to identify flow rates and seasonal trends.

Comparative analyses with historical data from previous monitoring periods (1980-1989) were conducted to ascertain trends in water quality degradation and changes in pollutant concentrations over time. Risk assessments based on observed pollutant levels were performed to quantify environmental risks related to water and sediment contamination in the Okchu River. Strategies for ecological flow management were proposed to mitigate the impact of reduced water quality, including the establishment of reservoirs to store cleaner water and controlled releases to maintain necessary ecological flow rates.

Results and Discussion

The Okchu River is 83 km long with a catchment area of 1,175 km². It flows through a region with significant industrial activity, primarily mining. Historical hydrological observations conducted from 1946 to 1988 indicated that the river is unsuitable for water supply. The river's average annual discharge is estimated at 11.2 cubic meters per second, with an annual volume of approximately 353.7 million cubic meters, largely influenced by snow (46%), rain (10%), and groundwater (44%).

Monitoring data revealed alarming concentrations of heavy metals in the river water, including copper-molybdenum compounds that are significantly above acceptable limits. The river's fauna has been decimated, with severe health risks for communities relying on it for water supply and irrigation. The Ministry of Ecology and Natural Resources reported that the levels of heavy metals and biogenic substances in the Okchu River have consistently exceeded normative values [20].

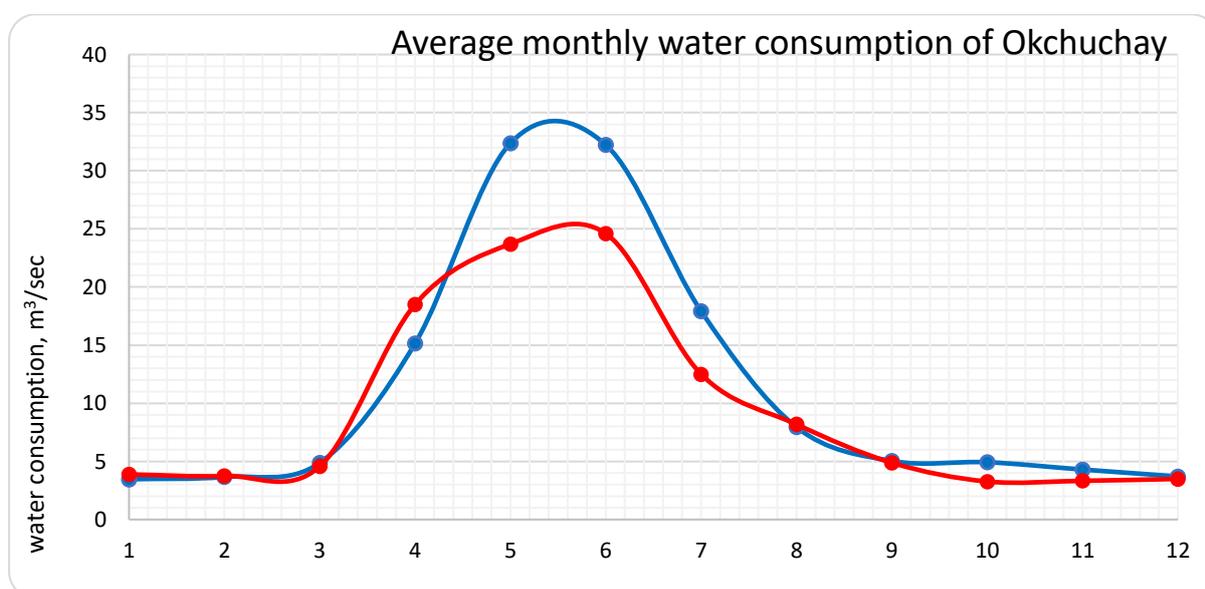


Fig. 1. Average monthly water consumption of Okchuchay

Nestled within the basin of the Okchu River, a vital tributary of the Araz River, the industrial hubs of Gafan and Gajaran play a pivotal role in Armenia's mining landscape. However, this significant waterway has faced substantial environmental challenges over the years, primarily due to the effluents released by the Gajaran copper-molybdenum and Gafan ore processing facilities. The pollution stemming from these industrial activities has resulted in alarming concentrations of heavy metals – such as copper, molybdenum, manganese, iron, zinc, and chromium – endangering both aquatic life and human health.

Recent assessments conducted by the Ministry of Ecology and Natural Resources of Azerbaijan have underscored the gravity of the situation. Findings indicate that copper-molybdenum levels in the river exceed acceptable limits by double, while iron

and nickel concentrations soar to four and seven times the permissible thresholds, respectively. Such figures illustrate the urgent need for intervention to mitigate the adverse effects on the river's ecosystem and surrounding communities [24].

Analysis of Pollutant Variation Dynamics in the Aquatic Environment Based on Water Samples Collected from the Oxchuchay River in 2023 (Shayıflı Station)

According to the results of water sample analyses conducted in 2023 from the Oxchuchay River, the variation dynamics of pollutants in the aquatic environment were monitored at ten-day intervals. At the Shayıflı station, samples were collected three times per month – during each ten-day period – and analyzed to assess changes in pollutant concentrations throughout the year [17].

Based on the analysis of monthly changes in

Table 1

Monthly Dynamics of Water Pollutants in Shayıflı Station (2023)

Month	Hardness			Ammonium (NH ₄)			Manganese (Mn)			Molybdenum (Mo)			Iron (Fe)			Sulfate (SO ₄)		
	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
January	–	16.4	16.5	–	0.0	1.3	–	144	574	–	164	308	–	392	908	–	372	586
February	17.1	14.0	10.0	1.3	1.2	2.4	438	642	674	233	247	674	638	808	811	498	476	277
March	10.6	10.8	9.9	1.5	1.6	1.6	427	386	625	234	170	233	875	104	183	372	381	247
April	11.8	8.4	7.6	0.0	0.0	0.0	163	175	153	95.4	202	219	223	886	664	205	104	200
May	8.8	8.4	6.0	0.0	0.0	0.0	414	319	158	234	204	122	203	111	946	212	294	171
June	3.1	3.89	4.2	0.0	0.0	0.0	212	170	143	38.5	44.4	65	154	705	444	93	133	141
July	4.86	6.0	6.9	0.0	0.0	0.0	325	102	238	135	143	245	181	511	101	129	205	217
August	7.3	7.76	8.3	0.0	0.2	0.0	125	19.8	34.8	221	248	237	564	34.1	58.9	213	225	253
September	8.2	8.1	8.0	0.1	0.0	0.0	11.2	10.8	7.5	263	141	94.9	40.5	77.1	44.5	251	257	372
October	9.69	8.33	10.1	0.0	0.0	0.0	35.8	142.7	20.5	153	126	170	53.1	51	37.7	359	390	403
November	10.45	12.5	12.4	0.0	0.0	1.1	8.1	276	140	73.5	273	114	8.1	162	76.6	348	476	498
December	11.4	9.23	11.0	0.0	0.4	0.0	200	35	45.8	295	237	277	161	87.7	751	400	272	365

Note: The Maximum Allowable Concentration (MPC) levels used for reference: Hardness = 7, NH₄ = 0.5, Mn = 0.1, Mo = 250, Fe = 300, SO₄ = 500 (units depending on substance, typically mg/L).

pollutant concentrations at the Shayıflı monitoring station in 2023, the following key results were observed:

- **Ammonium (NH₄) and Manganese (Mn) consistently exceeded acceptable limits** during multiple 10-day periods, with ammonium peaking at 2.4 mg/L in February (4.8 times the MPC) and manganese reaching up to 674 µg/L in the same month (6.74 times the MPC), indicating significant episodic contamination.
- **Iron (Fe) concentrations showed the highest fluctuation**, with levels peaking at 946 µg/L in May (over 3 times the MPC) and dropping as low as 37.7 µg/L in October, reflecting irregular but intense pollution events.
- **Hardness and sulfate levels, while mostly within regulatory limits, displayed notable seasonal trends**, with higher hardness observed in the winter months and sulfate peaking in

spring and late autumn, suggesting variability influenced by climatic and hydrological factors

Throughout 2023, a total of 108 water samples were collected from the Oxchuchay River, and 1,728 physico-chemical analyses were conducted. Additionally, to assess pollution levels, 39 bottom sediment samples were collected, which underwent 398 physico-chemical and 3 ecotoxicological analyses for the determination of heavy metals. The results indicate that the concentrations of iron, zinc, copper, and manganese were notably higher compared to other metals [21].

Results of Hydrobiological Monitoring Conducted in the Oxchuchay River

In 2023, hydrobiological monitoring was conducted in the Oxchuchay River during the spring, summer, and autumn seasons – specifically in April, June, and October – with the aim of studying the river's hydrofauna. As part of the monitoring pro-

cess, a total of four macroinvertebrate samples were collected from the upper, middle, and lower reaches of the river. Species identification and subsequent analyses were carried out by "Azelab" LLC [18].

According to the analysis results:

- In samples collected in April, 13 macroinvertebrate species belonging to the classes *Insecta* and *Annelida* were identified. Among these species:
 - 4 were classified as meso-saprobic, indicating suitability for moderately polluted waters.
 - 9 were identified as polysaprobic species, which are typically found in heavily polluted waters.
- In the samples collected in June, a total of 243 macroinvertebrate individuals belonging to *Insecta* and *Annelida* were recorded. Analysis of these samples revealed:
 - 3 species of oligosaprobic macroinvertebrates (total count: 45), typically inhabiting slightly polluted waters.
 - 4 species of meso-saprobic macroinvertebrates (count: 195), found in moderately polluted waters.
 - 1 polysaprobic macroinvertebrate species from the class *Annelida* (count: 3), indicating high pollution.
- In October, 57 macroinvertebrate individuals belonging to the class *Insecta* were identified. Among them:
 - 5 species were classified as oligo- and oligo-meso-saprobic, typically found in clean to slightly polluted waters, totaling 23 individuals.
 - 2 meso-saprobic species were identified, inhabiting moderately polluted waters, totaling 26 individuals.
 - 1 polysaprobic species, characteristic of highly polluted waters, was recorded with a total count of 8 individuals [13].

These findings illustrate the diversity of macroinvertebrate species corresponding to various pollution levels in the river ecosystem. Each species identified is considered an indicator organism adap-

ted to specific pollution conditions. Research also shows that certain organisms, such as members of the family *Hydropsychidae* from the order *Trichoptera*, typically found in clean waters, may adapt to moderately or heavily polluted environments in the absence of suitable habitats. This adaptive capacity is indicative of broader biological resilience in response to fluctuating environmental conditions [26].

In order to ensure continuous monitoring of the river's ecological stability, daily monitoring activities were conducted from February 2 to February 10, 2024. During this period, water samples were collected at various times throughout the day and subjected to appropriate laboratory analyses to determine the level of pollution (Table 2).

Based on the analysis of the results:

- At the Jahangirbeyli station (lower reaches), hardness exceeded the permissible concentration by a factor of 1.9, ammonium ion by 3.2 times, and manganese – a heavy metal – by 2.2 times.
- At the Shayifli station (middle reaches), hardness exceeded the limit by a factor of 2.0, ammonium ion by 4.4 times, and manganese by 3.2 times.
- At the Burunlu station (upper reaches), hardness was found to be 2.0–2.4 times, ammonium ion 3.0–4.4 times, and manganese 1.2–3.3 times higher than the permissible concentration limits.

The graphs below illustrate the indicators that exceeded the permissible concentration limits in the water samples collected throughout 2024 from the Burunlu station (located in the upper reaches of the Oxchuchay River, near the border) [13].

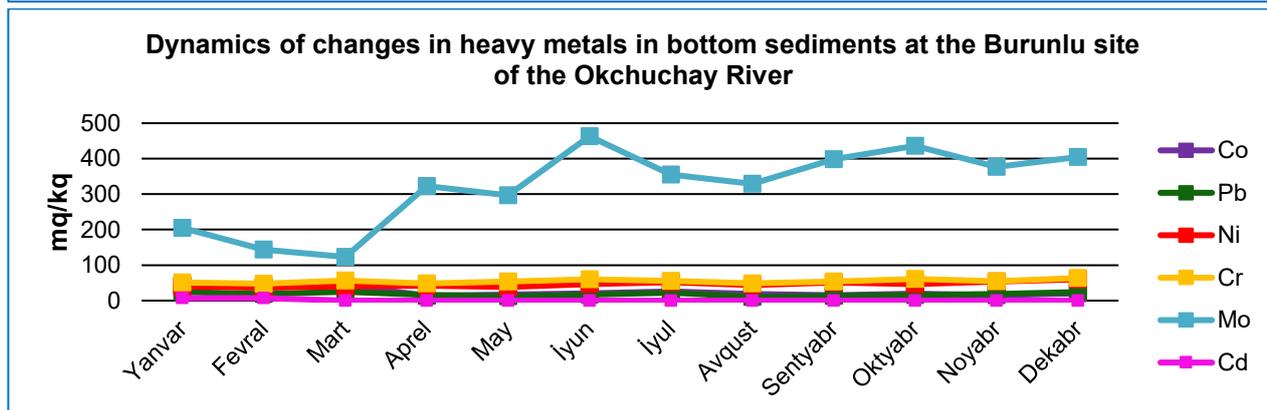
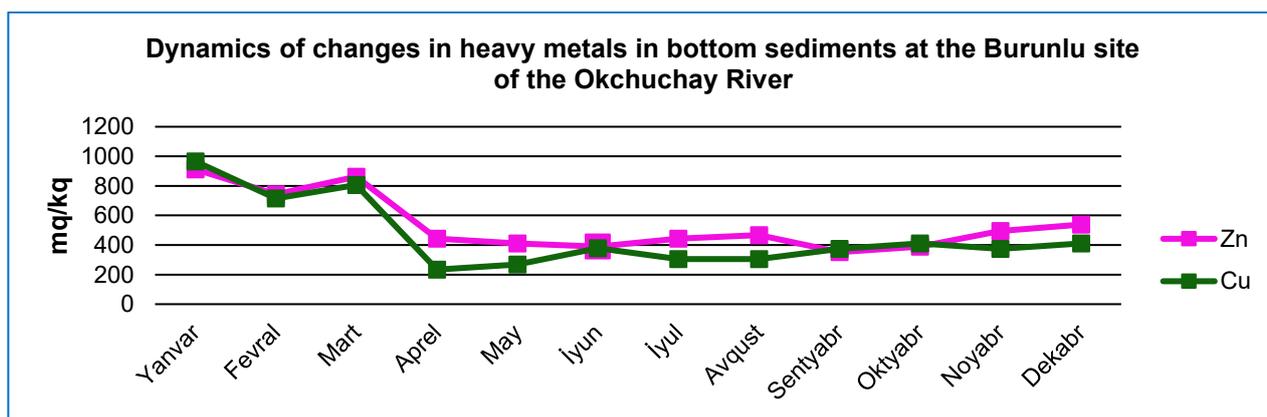
As illustrated in the graphs, a decrease in the concentration of pollutant components was observed in the samples collected from various stations along the Oxchuchay River during the April–September period of the current year. However, beginning in the second ten-day period of September, increases in the concentrations of certain pollutants were recorded.

Based on the analysis results of bottom sediment samples collected in 2024 from the Burunlu station (located in the upper reaches of the Okchu-

Table 2

Daily monitoring activities results from February 2 to 10,2024 in the Burunlu station (located in the upper reaches of the Oxchuchay River)

Compo-nents	02.02.24	05.02.24			06.02.24				09.02.24				10.02.24		
		14:20	18:00	19:30	10:30	13:30	15:30	16:15	13:50	16:00	17:00	01:30	07:45	16:00	18:00
pH	7,2	6,9	6,91	6,9	7	6,9	6,9	6,88	7,53	7,39	7,35	7,33	7,32	7,44	7,47
Zn	63,7	25,4	1,1	0,4	58,8	72,8	67,8	50	32	28,9	29,2	41,6	45	26	29,3
Fe	68,3	36,3	2,6	LOD	67,7	92,9	90,3	79,3	56,1	66,3	82,1	232	272	165,0	169,0
Pb	0,443	0,173	0,145	0,207	0,125	0,135	0,143	0,157	0,667	0,13	0,183	0,128	0,836	0,162	0,429
Ni	0,4	7,0	4,4	6,9	0,962	3,23	0,393	1,89	0,978	LOD	3,07	2,3	5,24	2,72	2,64
Mo	222,0	159,0	61,7	13,6	235	257	256	217	167	142	149	47,8	39,1	59,3	76,3
Mn	328,0	118,0	16,6	8,2	295	284	271	251	219	187	254	208	218	218	235
Cu	12,5	44,8	4,3	0,1	10,6	16,8	13	16,8	6,52	10,9	11,5	32,8	11,9	27,8	19,4



A promising avenue for addressing these issues lies in the effective utilization of the Okchuchay River's hydropower potential. This dual-purpose initiative aims not only to safeguard the river's ecosystem but also to harness its energy capabilities. To facilitate ongoing water quality monitoring, it is essential to deploy specialized automated systems at the river's entry into our republic. Complementing this technological upgrade, the construction of a regulating reservoir with a capacity of 3-4 million cubic meters at an elevation of 630 meters will allow for enhanced flow management. Water diverted from the main channel through a DN2200 mm pipe will be directed to the "Zangilan-1" Hydropower Plant, strategically located near Zangilan city at 465 meters elevation, boasting a total installed capacity of 9.5 MW.

Projected Energy Generation

The implementation of this hydropower project is expected to yield approximately 120-140 million kWh of electricity annually. Water from this facility will initially flow to the forthcoming "Zangilan-2" Hydropower Plant, set to be constructed at an elevation of 300 meters along the Araz River, utilizing a DN2200 mm diameter pipeline over a distance of 17.0 km. It is projected that this Small Hydropower Plant will generate an additional 70 million kWh of energy annually, thus providing reliable 'Green Energy' to over 90,000 residents [9, 10, 11].

The operational framework of these plants will capitalize on river overflow conditions from April to

July, with expected water discharges ranging from 18-20 m³/sec. However, limitations during May and June will restrict the diversion to 10 m³/sec. The remaining river flow will be redirected into the Araz River via the hydropower stations, thereby improving the overall water quality and benefiting the river's ecosystem.

To further enhance the ecological integrity of the Okchu River, a portion of the water collected in the intake reservoir will be channeled via a 5.3 km DN1600 mm pipeline to the 'Shayifli' reservoir, positioned outside the river channel. This reservoir will serve as a means to reintroduce purified water back into the river system, ensuring a sustainable ecological flow that protects both surface and underground water resources.

The successful execution of this project holds the potential to significantly mitigate the ecological crisis currently afflicting the river while simultaneously generating substantial electrical output. Currently, four small hydropower stations are under construction to capitalize on the hydropower potential of the Okchuchay River, marking a pivotal step toward sustainable resource management.

Comprehensive Hydropower and Ecosystem Conservation Strategy for the Okchu River:

- The Okchu River, a vital waterway in the Republic of Armenia, is currently facing significant ecological challenges due to heavy metal contamination along its 30 km stretch. Immediate and effective action is imperative to safe-

guard the river's ecosystem and restore its health.

- **Proposed Hydropower Developments:** To enhance the protection of the river's environment, a strategic plan involving the establishment of hydropower plants (HPPs) with a total capacity of 40 MW is under consideration. This initiative involves diverting the primary flow of the river through a specially constructed derivation pipe that runs parallel to the river's channel.
- **Optimizing Hydropower Potential:** This innovative approach to hydropower development not only aims to harness the river's energy potential but also ensures that 80-90% of its flow is redirected and subsequently released into the Araz River. Such an arrangement promises to maximize energy generation while prioritizing ecological stability.
- **Innovative Water Management Solutions:** To further enhance ecosystem protection, the installation of advanced river monitoring sensors is recommended. These sensors will enable the identification of periods when the river exhibits relatively cleaner water flow. During these optimal times, water can be collected in an auxiliary reservoir, which will later be utilized to maintain ecological flow within the river channel.
- **Construction of the Shayifli Reservoir:** A proposed reservoir with a capacity of 35 million cubic meters will be situated on the right bank of the Shayifli tributary, strategically located outside the main flow of the river. By utilizing the cleaner water from the Okchu River to fill this reservoir, we can ensure a consistent and regulated ecological flow ($Q_{eko} \approx 1.5-2.0 \text{ m}^3/\text{sec}$) is maintained in the river's natural course

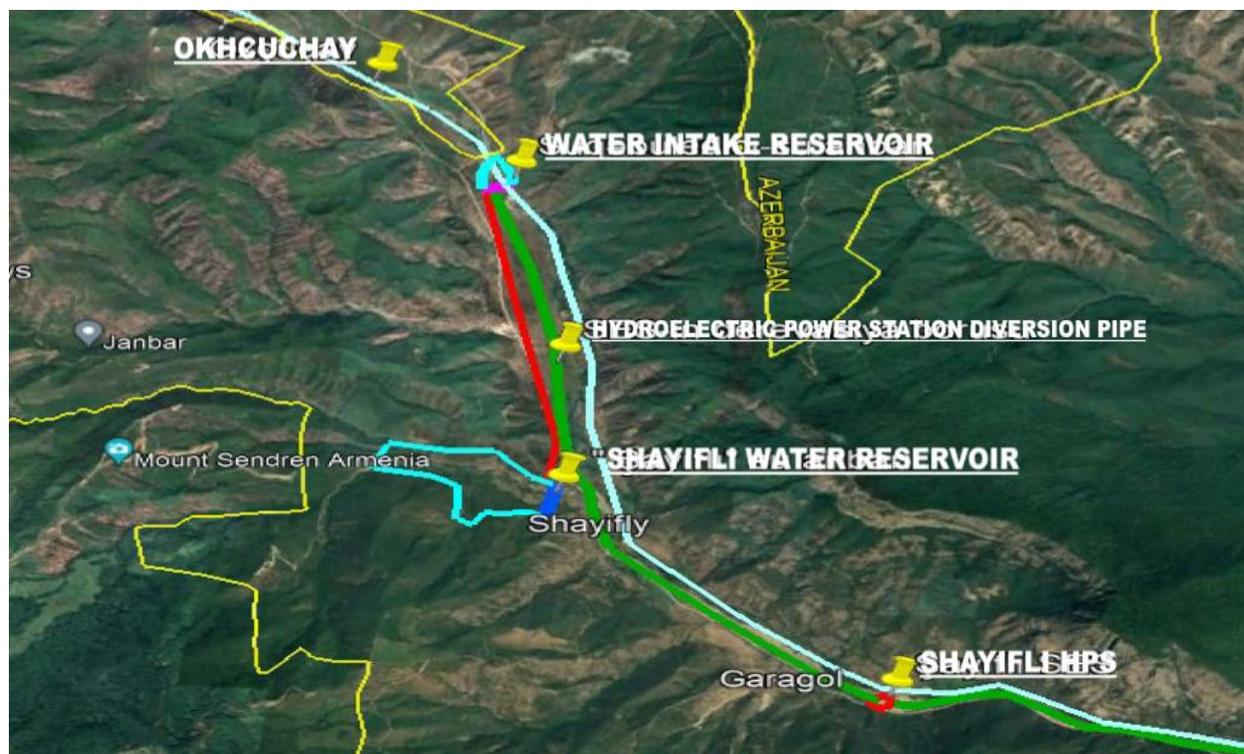


Fig. 2. Plan of facilities to be created for ecosystem protection in Okchu River

Conclusion

The Okchu River stands as a crucial water resource within the region, yet its severe industrial pollution has rendered it one of the most contaminated rivers globally. The ongoing pollution of the Okchu River has resulted in a significant decline in biodiversity, particularly in fish populations, due to toxic water inflow. The relentless discharge of untreated industrial effluents from copper-molybdenum mining operations has severely degraded water quality, jeopardizing aquatic life and posing substantial health risks to human populations. Effective management strategies are imperative to combat further pollution and restore the river's water quality.

Prioritizing the river's hydropower potential over its compromised water supply function offers a viable pathway for sustainable resource management. Continued cooperation between Armenia and Azerbaijan is essential to address transboundary pollution challenges and ensure the long-term sustainability of this vital natural resource for future generations.

In conclusion, the strategic integration of hydropower development with ecological preservation measures will not only address the immediate environmental concerns but also promote a sustainable future for the Okchu River and its surrounding communities.

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Деградація водної екосистеми внаслідок промислового забруднення: дослідження річки Окчу

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У статті пропонується комплексна стратегія розвитку гідроенергетичних ресурсів вздовж річки Окчу в Азербайджані з одночасним вирішенням екологічних проблем. Вона спрямована на відновлення здоров'я річки шляхом поєднання розвитку гідроенергетики з коригувальними екологічними заходами, забезпечуючи баланс між виробництвом енергії та екологічною стійкістю. У дослідженні використовуються історичні та сучасні набори даних, включаючи оцінки якості води та осаду, що підтверджуються екологічним моніторингом, що проводиться азербайджанськими та міжнародними організаціями. Аналітичні підходи використовуються для вимірювання концентрацій важких металів, зокрема міді, заліза та нікелю, та для оцінки їх екологічних наслідків для екосистеми річки та підземних водних ресурсів. Результати дослідження показали, що концентрації заліза, цинку, міді та марганцю були значно вищими, ніж у інших металів. Результати дослідження показують, що концентрації міді та молібдену значно перевищують допустимі межі, що загрожує безпеці питної води, сільськогосподарському зрошенню та водним організмам. Моніторинг на станції Шайїфлі у 2023 році виявив часті перевищення амонію (до 2,4 мг/л, 4,8× ГДК) та марганцю (до 674 мкг/л, 6,74× ГДК), що свідчить про епізодичне забруднення. Рівень заліза коливався в широких межах, досягнувши піку в 946 мкг/л (3× ГДК) у травні та знизившись до 37,7 мкг/л у жовтні. Жорсткість та сульфати залишалися переважно в межах норми, але демонстрували чіткі сезонні тенденції, пов'язані з кліматичними та гідрологічними факторами. Дослідження підкреслює погіршення екологічного стану річки Окчу, а також представляє план розвитку гідроенергетики, який, як очікується, вироблятиме 120–140 мільйонів кВт·год щорічно, доповнений додатковими 70 мільйонами кВт·год від нової гідроелектростанції. Для захисту екологічного стоку пропонується 5,3-кілометровий трубопровід очищеної води до водосховища Шайїфлі, а також інноваційні методи управління водними ресурсами та передові системи моніторингу. Це дослідження представляє інтегровану структуру, яка надає пріоритет сталому виробництву гідроенергетики разом з екологічним відновленням. Поєднуючи транскордонну співпрацю, передові технології моніторингу та управління екологічним стоком, воно окреслює модель балансування промислового розвитку з нагальною потребою в захисті навколишнього середовища в транскордонних річкових системах.

Ключові слова: хімічні параметри води, екосистема, гідроенергетика, водні ресурси, забруднення важкими металами, моніторинг річок, методи очищення, екологічна оцінка; моніторинг якості води.

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