International Journal on
Technical and Physical Problems of Engineering
(IJTPE)
Published by International Organization of IOTPE

ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com

December 2025 | Issue 65 | Volume 17 | Number 4 | Pages 472-481

# INTEGRATED EVALUATION OF RIVER WATER QUALITY, AQUATIC ECOSYSTEM HEALTH, AND RENEWABLE ENERGY POTENTIAL

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**Abstract-** The present study carried out within the framework of establishing a green energy zone in the recently liberated territories of Azerbaijan, investigates the effects of industrial wastewater contamination on the aquatic ecosystems of the Hakari and Bargushad rivers, with particular emphasis on pollutant inputs originating from the Okhchu River. The Okhchu River, primarily contaminated by effluents from copper-molybdenum production in neighbored countries, contributes to significant fish mortality events in its territory and Khudafarin Reservoir. Systematic monitoring and analytical assessments have revealed that contamination of water resources by heavy metals has a detrimental impact on biodiversity, leading to the degradation of riverine ecosystems and limiting their sustainable use for renewable energy purposes within the region. In response to these challenges, the study proposes the creation of fish farming reservoirs along the clean watercourses of the Hakari and Bargushad rivers, prior to their confluence with the Khudafarin Reservoir. These reservoirs would help shield the region's clean waters from contamination, support the recovery of native fish species, and provide additional benefits such as irrigation and hydropower generation and will enhance aquaculture production and support the preservation of native fish species. To address the ongoing pollution and protect these ecosystems, the study proposes creating new reservoirs on the Hakari and Bargushad rivers. In particular, the proposed "Hakari-Bargushad" reservoir would serve as a key environmental safeguard by preventing polluted Okhchu river water from reaching sensitive habitats. Overall, the findings emphasize an urgent need for coordinated environmental protection, improved monitoring, and sustainable water management to restore and preserve the region's valuable freshwater resources. Furthermore, the study highlights the potential for hydroelectric power generation in these areas, demonstrating the dual environmental and economic benefits of the proposed infrastructure. This strategy will not only improve water quality and fish stocks but also offer opportunities for water conservation and agricultural irrigation, ensuring the long-term sustainability of the river ecosystems. Research findings indicate that the environmentally responsible planning of hydropower infrastructure, along with its integration into a comprehensive renewable energy framework-encompassing solar and wind energy-in the liberated territories of Azerbaijan necessitates a strong emphasis on maintaining water quality, protecting fish populations, and ensuring long-term ecological integrity of river systems.

**Keywords**: Aquatic Biodiversity, Fish Mortality Events, Industrial Wastewater Contamination, Renewable Energy, Fish Farming Reservoirs, Water quality Monitoring.

## 1. INTRODUCTION

River systems play a critical role in sustaining ecosystems, supporting freshwater supply, enabling energy production, and maintaining socio-economic stability. In regions experiencing intensive anthropogenic pressure, river water quality degradation has become a major challenge, particularly due to the accumulation of heavy metals and other persistent pollutants. These contaminants adversely affect aquatic ecosystems, reduce fish populations, and limit the sustainable utilization of water resources.

In recently liberated territories of Azerbaijan, several strategically important rivers are characterized by elevated pollution levels and unstable hadrochemical conditions. Although these rivers serve as essential sources of freshwater and ecological services, their suitability for integrated utilization-such as hydropower generation, fisheries development, and environmental protection—has not been sufficiently evaluated. Existing studies largely focus on isolated water quality parameters or biological indicators, while the combined effects of heavy metal contamination, hydrological regulation, and engineering interventions remain poorly understood.

In particular, the interaction between highly polluted rivers, such as the Okhchu River, and comparatively cleaner systems, including the Hakari and Bargushad rivers, has not been systematically assessed. The absence of post-liberation, comparative analyses limit the development of effective engineering solutions for pollution buffering, reservoir planning, and aquatic ecosystem recovery. Moreover, previous research has not adequately explored the feasibility of integrating hydropower production, fish resource regeneration, and water quality management within a unified reservoir system. [8]

Registered: 290828 Article Info: 260130 Accepted: 251123
Reserved: 251006 Available: 251231

The present study addresses these gaps by providing a comprehensive post-liberation assessment of the physicochemical properties and heavy metal concentrations of the Okhchu, Bargushad, and Hakari rivers. The novelty of this work lies in its integrated approach, which links water quality and ecological indicators with engineering-based strategies for reservoir design and fish habitat restoration. Special attention is given to the concept of an intermediate Hakari-Bargushad reservoir aimed at isolating polluted inflows, protecting downstream systems, and creating controlled conditions for fish breeding and migration.

- The objectives of this study are to: evaluate and compare the physicochemical and heavy metal characteristics of the selected rivers;
- assess the ecological implications of observed pollution levels, particularly in relation to fish mortality and biodiversity loss;
- analyze engineering constraints and opportunities for pollution control and water quality stabilization through regulated reservoirs;
- propose an integrated framework for sustainable hydropower development, fisheries regeneration, and environmental management.

The results of this research contribute to engineering science and environmental management by providing a scientifically grounded basis for the design of multi-purpose reservoir systems that support renewable energy production, aquatic ecosystem recovery, and long-term sustainable water resource utilization

## 2. MATERIALS AND METHODS

Systematic sampling and analysis of water and sediment were initiated in 2021 along the Okhchu River and other regional rivers to assess water quality and pollution levels. Sampling was conducted at three distinct locations along the Okhchu River's flow trajectory. In 2023, monitoring efforts focused on the Okhchu River included the collection of 108 water samples from the upper, middle, and lower reaches. These samples underwent a total of 1,728 physicochemical analyses. Furthermore, to evaluate pollution levels, 39 sediment samples were collected, and 398 physicochemical analyses were performed to quantify heavy metal concentrations. Additionally, three ecotoxicological tests were conducted. Laboratory results indicated that concentrations of iron, zinc, copper and manganese were comparatively higher than those of other assessed heavy metals.

Quarterly monitoring of the Hakari River was conducted at the Balasoltanli station in Gubadli District. A total of four water samples were collected during the year, and these underwent 70 physicochemical analyses performed by Azelab LLC. A water sample was collected from the Lachin Boulevard area on April 13, 2024, and subsequently submitted for laboratory analysis at the Azecolab facility on April 15, 2024 (sample identification number: 21032-01).

Between January and August 2024, the Okhchu River was monitored comprehensively across its upper, middle, and lower reaches. This resulted in the collection of 91 water samples, with 1,474 physicochemical analyses conducted. Sediment sampling during this period yielded additional insights into pollution levels, with 240 analyses targeting heavy metal concentrations.

In a similar monitoring effort, the Bargushad River was sampled at ten-day intervals over an eight-month period. This campaign resulted in the collection of 72 water samples and the performance of 1,170 physicochemical analyses. Additionally, 24 sediment samples were obtained, and 240 analyses of heavy metal content were carried out by Azelab LLC. The findings revealed that iron, zinc, copper and manganese were the predominant metals in terms of concentration. For the Hakari River, quarterly monitoring activities from January to August 2024 involved the collection of three water samples. These samples underwent 49 physicochemical analyses to evaluate water quality and pollution indicators.

## 3. RESULTS AND DISCUSSION

Fish Species Inhabiting the Karabakh. The ichthyofauna of Karabakh has been predominantly studied during the mid-20th century. The most recent comprehensive scientific data on fish species inhabiting the region dates back to the 1970s, before the occupation period [12].

In total, 23 fish species belonging to four families-Cyprinidae, Salmonidae, Gobiidae, and Nemacheilidae-have been recorded. Approximately 75% of these species are from the Cyprinidae family, which includes semi-migratory species characterized by high diversity (17 out of 23 species). Other families include Salmonidae (e.g., river trout, Angora loach, and Kura loach), Gobiidae (e.g., Caucasian goby and golden goby), and Nemacheilidae (e.g., Caucasian stream loach). [15]

Karabakh's freshwater systems are home to 20 fish species, excluding the river trout, Kura nase (Chondrostoma cyri), and South Caucasus stone loach.

In the section of the Kondalan River flowing through Khojavend and Fuzuli districts, 14 species have been identified, including species like the Caucasian khramulya (Capoeta sevangi) Kura barbel, and Transcaucasian goby.

- The Gargar River in Agdam District contains eight fish species, including the Kura loach and Caucasian stream loach.
- The Tartar River, including the Sugovushan Reservoir in Tartar District, supports 14 fish species, such as the Angora loach and golden goby.

The aquatic systems of these regions are home to 22 fish species, excluding the Kura khramulya *(Capoeta capoeta)*. Key rivers in this region include the Basit, Okhchu, and Hakari rivers, which host species like the river trout, Caucasian stream loach, and Transcaucasian goby.

- In the Lachin and Gubadli districts, 10 species inhabit the Hakari River, including the Kura loach and Angora loach.
- In the Kelbajar District, the Tartar River and Sarsang Reservoir harbor six species, including the river trout and Kura barbel.

Fish species listed in Azerbaijan's "Red Book" are notably present in these regions. The river trout is found in the upper reaches of the Tartar, Hakari, and Basit rivers, as well as in the Sarsang Reservoir. The golden bleak, another "Red Book" species, is distributed across the Basit, Okhchu, and Hakari rivers in Zangilan, Lachin, and Gubadli districts, as well as the upper reaches of the Kondalan River in Khojaly and Fuzuli districts.

In the lower reaches of the Araz River tributaries, the khramulya is the dominant species, followed by abundant populations of bleak and barbel. The ichthyofauna of the Gargar River and its tributaries, such as Khojaly River, is similar to that of the Kondalan River, with species like the Kura silverfish, Caucasian khramulya, and Transcaucasian goby being prominent [16].

This comprehensive overview highlights the significant biodiversity of fish species in the Karabakh, emphasizing their ecological and conservation value.

In March 2021, a massive fish death (Small Trout) was recorded in the river. During the investigations conducted in the Shayifli and Jahangirbeyli basins of the Okhchu River in Zangilan discovered the mass death of 227 goldfish and 330 shirbit fish included in the "Red Book" of Azerbaijan took place here [3].

This situation explains both the necessity and the opportunity to restore fish species in order to preserve and sustainably utilize these natural water resources. Prolonged pollution, uncontrolled discharges, habitat fragmentation, and hydrological alterations have led to a significant decline in fish reserves in the Hakari-Bargushad river system. Elevated concentrations of heavy metals and suspended solids, combined with seasonal flow instability, have negatively affected fish spawning grounds, juvenile survival rates, and overall biodiversity.

From an engineering perspective, the planned Hakari-Bargushad reservoir system provides a strategic platform for fish stock regeneration and sustainable fisheries development. Reservoir regulation can stabilize flow regimes, reduce extreme hydrological fluctuations, and create controlled aquatic habitats suitable for both natural reproduction and managed aquaculture. The retention function of reservoirs also enables sediment and pollutant trapping, thereby improving downstream water quality and reducing toxic exposure to aquatic organisms.

## 4. MONITORING RESULTS OF THE OKHCHU RIVER

Monitoring activities conducted on the Okhchu River in 2021 identified significant levels of pollution, as evidenced by the results of chemical analyses. Samples collected at the border point of country exhibited heavy metal and biogenic substance concentrations that exceeded permissible thresholds. Specifically, ammonium concentrations were 1.6 times higher than the standard, while manganese, iron, nickel, cadmium, and molybdenum levels were 4.0, 4.5, 5.5, 2.9, and 1.9 times higher, respectively. Water samples obtained approximately 5 km downstream near Zangilan city displayed slightly reduced concentrations compared to the upper reaches. However, these values still exceeded permissible standards, with ammonium levels 1.3 times, manganese 3.6 times, and nickel 3.4 times above the acceptable limits. [9]

In March 2021, a substantial discharge of untreated wastewater into the river caused a large-scale fish die-off, highlighting the severe ecological consequences of the pollution. [1]

The facility discharges untreated waste from copper and molybdenum production directly into the river, resulting in contamination levels that significantly exceed ecological and health standards. These elevated pollution levels render the river's water resources unsuitable for use and contravene environmental regulations. A notable portion of this plant is owned by the German company Cronimet. Additionally, the Gafan Ore Processing Plant contributes further to the river's pollution through the release of heavy metals, compounding the environmental degradation. The cumulative effect of these pollutants not only devastates the river's aquatic ecosystem but also poses significant risks to human health. [8]

The consumption of water contaminated with heavy metals and other pollutants is associated with serious health risks. Documented impacts include gastrointestinal disorders, renal and skeletal tissue damage, as well as cardiovascular and neurological system dysfunctions. These findings underscore the urgent need for remediation measures to mitigate the environmental and public health hazards posed by the ongoing contamination of the Okhchu River.

The Okhchu River serves as a significant conduit for the disposal of waste generated by mining activities. The river's water quality has deteriorated to such an extent that it has become inhospitable to aquatic life, with no viable organisms able to survive in its highly polluted environment. Given that the Okhchu flows into the Araz River, the second largest watercourse in the South Caucasus, the contamination from the Okhchu River has substantial implications for the overall water quality of the Araz River.

The Araz River, a critical tributary of the Kura River, is fundamental to regional hydrology and constitutes the main source of irrigation for Azerbaijan's agricultural lands. However, recent significant declines in water quality in the Araz River -attributable in large part to the pollution from the Okhchu River- have resulted in adverse effects on both domestic water use and agricultural irrigation. These changes pose serious risks to public health and agricultural productivity, underscoring the need for urgent measures to address the ongoing contamination and restore the water quality of these interconnected river systems [7].

In 2024, an extensive assessment of water quality was carried out at the Shayifli monitoring station on the Okhchu River. This investigation involved the collection of 24 water samples and the execution of 390 associated physicochemical analyses. The findings indicated that contamination levels at this location exceeded established permissible concentration thresholds by factors ranging from 1.4 to 2.0, with the highest degree of pollution recorded during the second ten-day interval of March.

Elevated concentrations of ammonium ions ($NH_4^+$) were detected, surpassing allowable limits by approximately 1.8 to 4.4 times. Peak ammonium levels occurred during the second ten-day period of January and the first ten-day period of February. With respect to heavy metals, Manganese (Mn) concentrations exceeded permissible standards by 1.1 to 4.0 times, reaching maximum values in January. Increased levels of molybdenum (Mo) were also observed during January, ranging from 1.1 to 1.2 times above acceptable limits. Additionally, iron (Fe) concentrations surpassed regulatory thresholds by approximately 1.2 times during the third ten-day period of March.

Table 1. Analytical Results from the Okhchu River - Burunlu Region, Collected between February 2nd and 10th, 2024 [9]

| No | Component Name | Unit of Measurement | 02.02.24 | 03.02.24 | 05.02.24 | 06.02.24 | 09.02.24 | 10.02.24 |
|---|---|---|---|---|---|---|---|---|
| 1 | Hydrogen Index | pH | 7.2 | 7.13 | 6.9 | 7 | 7.35 | 7.44 |
| 2 | Dissolved Oxygen | $mgO_2/L$ | 5.4 | 6.7 | 4.8 | 4.2 | 7.4 | 9 |
| | | % | 54.0 | 67 | 52 | 47 | 82 | 99 |
| 3 | Electrical Conductivity | $x10^{-3}$ µcm/cm | 1547.0 | 1608 | 1691 | 1745 | 1264 | 706 |
| 4 | Chemical Oxygen Demand (COD) | mg-ekv/l | 14.0 | 14.6 | 16.19 | 16.42 | 10.35 | 6.12 |
| 5 | Chloride Ion, $Cl^-$ | mg/l | 20.6 | 19.14 | 19.49 | 19.14 | 16.31 | 14.9 |
| 6 | Sulfate Ion, $SO_4^{2-}$ | mg/l | 381.6 | 391.2 | 411.9 | 416.9 | 204.3 | 140 |
| 7 | Ammonium Ion, $NH_4^+$ | mg/l | 2.3 | 1.5 | 2.19 | 0.57 | 1.17 | 1.59 |
| 8 | Nitrite Ion, $NO_2^-$ | mg/l | 0.8 | 0.7 | 0.87 | 0.99 | 0.64 | 0.24 |
| 9 | Nitrate Ion, $NO_3^-$ | mg/l | 7.1 | 7.72 | 5.99 | 5.97 | 7.92 | 4.18 |
| 10 | Zinc, Zn | mkg/l | 63.7 | 79.3 | 25.4 | 58.8 | 29.2 | 35.1 |
| 11 | Iron, Fe | mkg/l | 68.3 | 143.0 | 36.3 | 67.7 | 82.1 | 213 |
| 12 | Lead,Pb | mkg/l | 0.443 | 0.938 | 0.173 | 0.125 | 0.183 | 0.141 |
| 13 | Nickel,Ni | mkg/l | 0.4 | 0.9 | 7.0 | 0.962 | 3.07 | 1.77 |
| 14 | Molybdenum, Mo | mkg/l | 222.0 | 226.0 | 159.0 | 235 | 149 | 39 |
| 15 | Manganese, Mn | mkg/l | 328.0 | 255.0 | 118.0 | 295 | 254 | 223 |
| 16 | Copper, Cu | mkg/l | 12.5 | 18.6 | 44.8 | 10.6 | 11.5 | 14.8 |

Particular concern, changes in the water environment were noted in February, when a foul odour emanated from the river and visible household and industrial waste was observed flowing from upstream sources. These changes prompted the initiation of intensive monitoring activities to assess the extent of pollution and its potential impact on the river's ecosystem and water quality. This ongoing monitoring effort aims to provide a clearer understanding of the pollution dynamics within the Okhchu River and inform future mitigation strategies.

From February 2nd to 10th, water samples were collected four times a day, at regular intervals, from the Burunlu region of the Okhchu River. These analyses were conducted on dates when the highest levels of contaminated water were discharged from neighbored country. As a result, it was confirmed that during copper-molybdenum production, untreated wastewater was directly discharged into the river, poisoning the local biodiversity. The daily results of the water quality analysis are summarized as follows [9]:

Throughout the monitoring period from January to August 2024, a total of 91 water samples were collected from the Okhchu River. Sediment sampling was also conducted, accompanied by 240 physicochemical analyses targeting heavy metal content. The results demonstrated that zinc, iron, manganese, and copper exhibited higher concentrations relative to other metals analyzed. These outcomes indicate notable spatial and temporal variability in contamination patterns, with these metals representing the dominant pollutants in both water and sediment matrices. The data provides critical insights into the extent of anthropogenic impact on the river's ecosystem, especially concerning the accumulation of heavy metals. Further studies and mitigation efforts are necessary to address these pollution levels and prevent further ecological degradation [11].

### 4.1. Bargushad River

The analysis of heavy metal concentrations in the Bargusad River for the Gubadli region from January to August reveals significant variations in levels. Below are the key findings based on the data collected:

Table 2. Summary of heavy metal concentrations in the Bargusad River (Gubadli Region) [11]

| | January | February | March | April | May | June | July | August |
|---|---|---|---|---|---|---|---|---|
| Mn | 788 | 788 | 644 | 691 | 573 | 545 | 536 | 612 |
| Co | 6.5 | 4.22 | 2.04 | 12.04 | 8.05 | 5.96 | 6.96 | 6.29 |
| Pb | 2.44 | 3.25 | 4.12 | 18.3 | 14.7 | 11.04 | 9.88 | 12.66 |
| Ni | 9.77 | 6.44 | 5.11 | 2.07 | 5.06 | 3.83 | 8.99 | 4.56 |
| Cr | 7.01 | 4.55 | 3.44 | 26.9 | 31 | 25.4 | 20.4 | 27.4 |
| Mo | 4.55 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Fe | 24630 | 29360 | 25320 | 23.5 | 24.68 | 28760 | 21890 | 24780 |
| Zn | 44.4 | 31.7 | 36.05 | 63.6 | 59.8 | 47.8 | 53.6 | 39.5 |
| Cu | 40.55 | 29.7 | 20.04 | 45.6 | 40.3 | 47.6 | 53.4 | 35.6 |

The Bargusad River demonstrates persistently elevated concentrations of manganese and iron, with levels consistently surpassing the established permissible limits (788 and 2936 respectively). This ongoing exceedance suggests significant ecological risks, potentially affecting aquatic life and the broader ecosystem. Additionally, a marked increase in lead concentrations during the month of April underscores the need for in-depth investigations to identify and assess the sources of contamination, as well as the pathways through which these pollutants may enter the river system. In contrast, concentrations of other heavy metals analyzed remain within the acceptable thresholds, indicating that the pollution may be localized rather than indicative of a region-wide issue. Given these findings, it is crucial to implement continuous monitoring to track pollution levels, assess trends, and inform mitigation strategies aimed at preserving the ecological integrity of the Bargusad River [11].

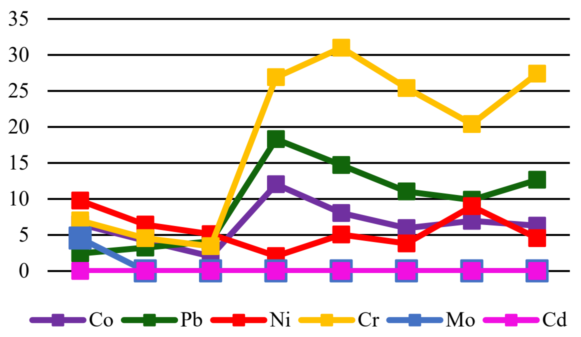


Figure 1. Dynamics of Heavy Metal Concentrations (mg/L) in the Bargusad River in Gubadli Region from January to August [11]
Co - Cobalt concentration Pb - Lead concentration
Ni - Nickel concentration Cr - Chromium concentration
Mo - Molybdenum concentration Cd - Cadmium concentration

### 4.2. Hakari River

In 2023, based on the analysis results from the Balasoltanli village area in the Gubadli region along the Hakari River, only the concentration of iron (Fe) exceeded the permissible threshold, reaching 2.9 times the allowable limit in the second quarter. All other determined indicators remained within the acceptable concentration levels. [11]

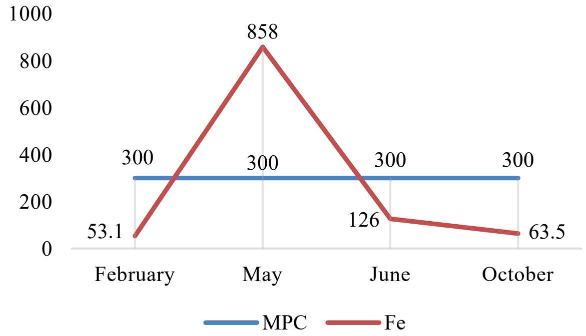


Figure 2. Change dynamics of Iron (Fe) in Hakari River's water environment for 2023 [16]

In January 2024, an analysis of river water was conducted in the laboratory of Azerbaijan Construction and Architectural University. The results indicated a turbidity of 1.04 NTU, measured using a turbidimeter; an electrical conductivity of 128.1 µS, determined with a conductometer; and a salinity of 0.1 ppt. On April 13, 2024, a water sample was collected from the area referred to as Lachin Boulevard and subsequently submitted for laboratory analysis at Azecolab on April 15, 2024 (sample identification number: 21032-01).

The analytical results indicated that the concentration of nickel (Ni), measured at 3.8 µg/L, exceeded the guideline value established by the World Health Organization (≤ 0.07 mg/L) and approached the maximum limit set by the United States Environmental Protection Agency (≤ 0.1 mg/L). Given the potential health implications associated with prolonged exposure to elevated nickel levels, it is imperative to address this issue. Nickel is a known carcinogen and can have detrimental effects on renal and respiratory systems, thus necessitating further investigation and remediation efforts [24].

Table 3. Parameters of some analysis taken from Lachin boulevard region [8]

| Test Parameter | Unit | Result | WHO Guideline | EPA Standard |
|---|---|---|---|---|
| $NO_3$ | mg/L | 1.7 | ≤ 50 mg/L | ≤ 10 mg/L |
| $SO_4$ | mg/L | 14.3 | ≤ 250 mg/L | ≤ 250 mg/L |
| Ni | µg/L | 3.8 | ≤ 0.07 mg/L | ≤ 0.1 mg/L |
| Cu | µg/L | 3.32 | ≤ 2.0 mg/L | ≤ 1.3 mg/L |
| Pb | µg/L | <0.01 | ≤ 0.01 mg/L | ≤ 0.015 mg/L |
| COD | mg/L | 6.01 | ≤ 25-50 mg/L | Not directly regulated |
| BOD5 | mg/L | 4.00 | ≤ 5-10 mg/L | Not directly regulated |

Similarly, copper (Cu) was detected at a concentration of 3.32 µg/L, surpassing both the WHO guideline (≤ 2.0 mg/L) and the EPA regulatory standard (≤ 1.3 mg/L). Excessive copper concentrations are associated with gastrointestinal disturbances, liver and kidney damage, and may also compromise water quality. Therefore, these elevated levels warrant immediate attention, including further investigation to identify potential sources of contamination and the implementation of appropriate remedial measures to mitigate the risks to public health and the environment.

In contrast, the concentration of lead (Pb) was determined to be below 0.01 µg/L, remaining well within the permissible limits prescribed by both the WHO and EPA. This finding is noteworthy given the high toxicity of lead and its pronounced health risks, particularly for sensitive population groups such as children and pregnant women [24]. The low lead concentration indicates minimal risk in terms of lead contamination, but continued vigilance is essential to ensure that levels remain below permissible thresholds.

While the majority of analyzed parameters remain within the safe limits set by regulatory bodies, particular attention must be given to the elevated concentrations of nickel and copper. Continuous monitoring is critical to track trends in metal contamination and to evaluate the efficacy of mitigation strategies. A combination of analytical techniques, including ion chromatography (IC), inductively coupled plasma mass spectrometry (ICP-MS), spectrophotometric methods, and respirometry methods, were employed to ensure comprehensive and accurate results.

Additionally, the limits of detection (LOD) and the associated measurement uncertainty (MU) were established in accordance with standard analytical protocols [24]. Further investigations are needed to identify potential pollution sources and implement corrective measures to safeguard water quality and public health in the long term. At the same time, pollution has negative impact for fisheries industry development in these territories.

Table 4. Methods of analysis [24]

| PP Code | Test Parameter | Test Unit | Ref Method | Technique | LOD | MU, % |
|---|---|---|---|---|---|---|
| 1380A04 | Nitrate ($NO_3$) | mg/L | ASTM_D4327 | IC | 0.016 | 9 |
| 1380A05 | Sulphate ($SO_4$) | mg/L | ASTM_D4327 | IC | 0.02 | 8 |
| 2005A18 | Nickel (Ni) | µg/L | EPA_6020B | ICP-MS | 0.02 | 2 |
| 2005A19 | Copper (Cu) | µg/L | EPA_6020B | ICP-MS | 0.11 | 2 |
| 2005A30 | Lead (Pb) | µg/L | EPA_6020B | ICP-MS | 0.01 | 2 |
| 3022A01 | COD | mg/L | ASTM_D1252B | Spectrophotometric | 4 | 11 |
| 3030A01 | $BOD_5$ | mg/L | SM_5210D | Respirometric | 1 | 14 |

### 4.3. Comparative Summary of Water Quality and Heavy Metal Characteristics

The hydrochemical and heavy metal analyses of the Okhchu, Bargushad, and Hakari rivers reveal distinct pollution patterns, temporal variability, and engineering implications for water resource management, reservoir planning, and fisheries development.

❖ Okhchu River

The Okhchu River exhibits unstable water quality conditions during the observation period (February 2024). Dissolved oxygen levels varied significantly (4.2-9.0 mg/L), with several measurements indicating suboptimal conditions for aquatic life, particularly during low-oxygen periods. Electrical conductivity and sulfate concentrations were consistently high, suggesting mineralized inflows and anthropogenic influence. Elevated concentrations of molybdenum (up to 235 µg/L), manganese (up to 328 µg/L), iron (up to 213 µg/L), and zinc indicate chronic heavy metal stress, which poses risks to fish health and limits natural reproduction. These characteristics classify the Okhchu River as a high-risk inflow source requiring treatment or isolation before integration into reservoir systems.

The Bargushad River demonstrates pronounced seasonal variability in heavy metal concentrations, with particularly high levels of iron (up to 29,360 µg/L), manganese (up to 788 µg/L), chromium (up to 31 µg/L), and lead (up to 18.3 µg/L) during spring and summer months. Such fluctuations reflect hydrological seasonality, sediment mobilization, and upstream contamination sources. Despite this variability, the predictable seasonal patterns provide an opportunity for engineering-based regulation, such as controlled sediment retention and flow management within a reservoir framework. The river shows potential for conditional utilization, provided that pollutant attenuation measures are applied.

In contrast, the Hakari River displays relatively favorable water quality conditions. All measured parameters remain within WHO and EPA guideline limits, including nitrate, sulfate, nickel, copper, and lead concentrations. COD and $BOD_5$ values indicate low organic pollution, supporting ecological stability and suitability for aquatic life. These results position the Hakari River as the most environmentally suitable component of the integrated Hakari-Bargushad reservoir system and a primary candidate for fish hatchery development and sustainable aquaculture operations.

### 4.4. Integrated Engineering Interpretation

❖ Comparative analysis indicates that:

- Okhchu River represents a pollution-dominated system requiring isolation, pre-treatment, or controlled inflow management.
- Bargushad River shows seasonally controllable pollution, suitable for engineering mitigation through sedimentation zones and regulated discharge.
- Hakari River provides a low-pollution, ecologically stable water source, ideal for fisheries regeneration and reservoir-based aquaculture.

From an engineering perspective, integrating these rivers within a regulated reservoir system enables pollution buffering, water quality stabilization, and ecological recovery. In particular, the polluted Okhchu River must be hydraulically isolated and prevented from directly contaminating the Khudafarin reservoir, as uncontrolled inflow would pose a serious risk to downstream water quality and aquatic ecosystems. To address this, it is critically important to construct an intermediate reservoir within the Hakari-Bargushad river system, functioning as a buffer and treatment zone that limits pollutant transfer, promotes sedimentation of heavy metals, and stabilizes physicochemical parameters.

This intermediate reservoir can be strategically designed as a fish regeneration and breeding zone, providing controlled environmental conditions suitable for spawning, juvenile development, and stock recovery. In addition, the incorporation of engineered fish migration corridors and fish passage structures would ensure ecological connectivity between river segments while preventing exposure of sensitive species to polluted inflows. Such a configuration allows selective water routing, where cleaner Hakari-Bargushad waters support aquaculture and biodiversity restoration, while contaminated Okhchu waters are managed separately through retention, dilution, or treatment mechanisms. This integrated engineering solution supports the development of a fish production plant, enhances long-term biodiversity conservation, protects the Khudafarin reservoir from secondary contamination, and ensures that hydropower generation is aligned with environmental sustainability and ecosystem resilience.

To mitigate fish resource losses and enhance regeneration capacity, several engineering solutions can be implemented:

- Fish hatchery and breeding facilities integrated with the reservoir infrastructure to support artificial spawning, larval rearing, and periodic restocking of native species.

- Selective water intake and discharge structures designed to maintain optimal temperature, dissolved oxygen, and flow conditions for fish survival.
- Sediment management and pre-reservoir settling zones to reduce heavy metal accumulation in biologically active areas.
- Fish passages and ecological corridors to maintain connectivity between river segments and prevent genetic isolation.
- Water quality monitoring and adaptive reservoir operation, allowing flow regulation strategies that align hydropower generation with ecological requirements.

The establishment of a fish production plant within the Hakari-Bargushad reservoir zone would not only compensate for past ecological losses but also contribute to long-term food security, biodiversity conservation, and socio-economic development. By integrating hydropower operation, water resource management, and fisheries engineering into a unified system, the reservoir can function as a multi-purpose infrastructure supporting both renewable energy generation and aquatic ecosystem recovery.

## 5. INTEGRATED UTILIZATION PLAN FOR THE WATER RESOURCES OF THE BARGUSHAD AND HAKARI RIVERS

Currently, the water resources of the Hakari and Bargushad Rivers are utilized to a very limited extent. Based on the hydrological confluence of the rivers, the annual water resource of the Bargushad River is estimated at 500 million cubic meters (excluding the 250 million cubic meters used in neighbored country's territory), while the annual water resource of the Hakari River is also estimated at 500 million cubic meters. Therefore, the total flow entering the Araz River from these rivers each year is approximately 1.0 billion cubic meters. [9]

The Bargushad River, with a length of 178 km and a drainage basin area of 2711 km² from Zalxa Lake located at an altitude of 3040 meters. The river enters the territory of Azerbaijan near the village of Eyvazlar in the Gubadli region, where it merges with the Hakari River near the village of Qaralar, and ultimately flows into the Araz River. At the point where it merges with the Hakari River, the average annual discharge of the river is 24.0 m³/s.

The Bargushad River is mainly regulated within Bordering country's territory before entering Azerbaijan, which results in minimal sedimentation and suspended matter in the river's flow, allowing clear water to enter the country. Seasonal fluctuations in the river's flow, especially in spring and autumn, are generally not significant. The sustainable utilization of the water resources of the Bargushad River in the following manner could facilitate rapid economic development in the region:

➢ Construction of the "Bakhtiyarli" reservoir near the Bakhtiyarli village, with a volume of up to 70 million cubic meters [9].

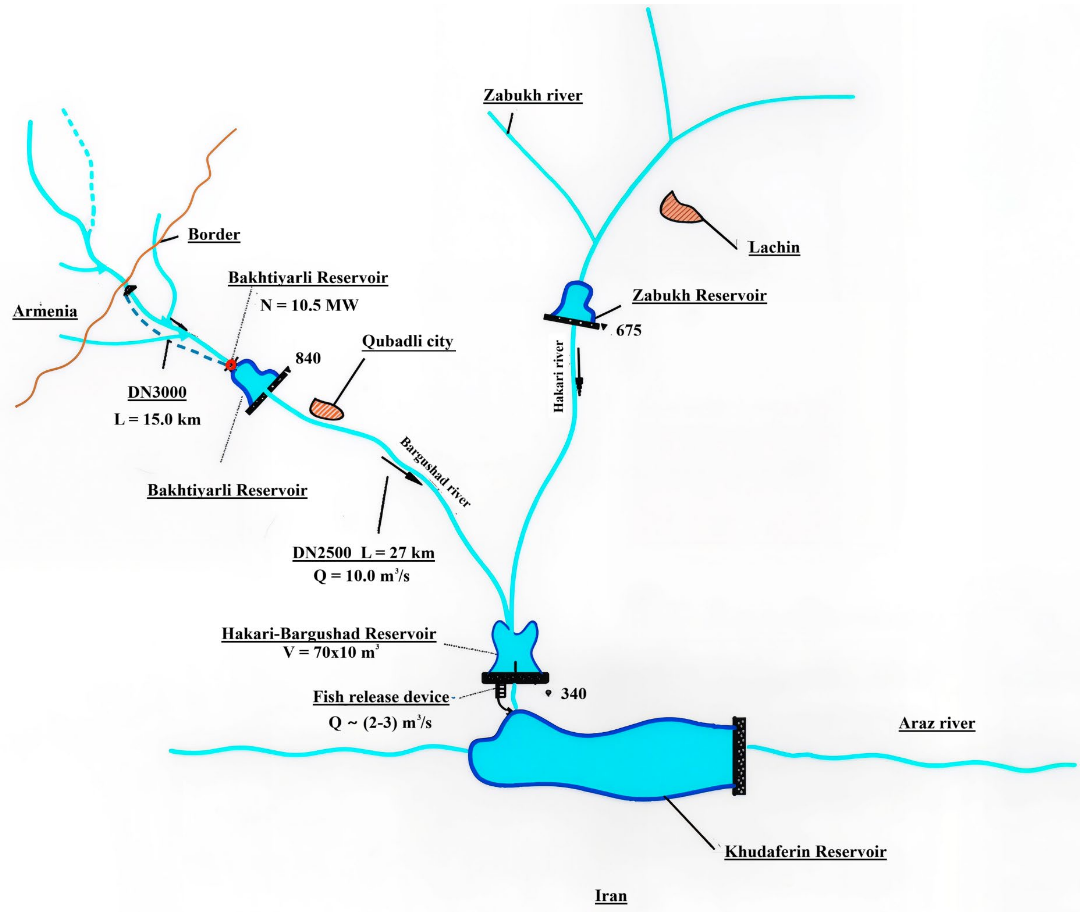


Figure 3. Strategic framework for the sustainable utilization of water resources from the Bargushad and Hakari rivers for fisheries enhancement [9]

- Construction of the "Bakhtiyarli-1" Hydroelectric Power Station (HPS) with a capacity of 10.5 MW using the 120.0 m drop in the riverbed between Eyvazli village and the Bakhtiyarli reservoir;
- Measures for utilizing up to 250.0 million cubic meters of the river's total water resource for ecosystem conservation and irrigation below the reservoir;
- Directing up to 250.0 million cubic meters of the river's water resource for the irrigation of agricultural lands in the Zangilan and Jabrail regions.
- These reservoirs will help to improve water quality for fishes which lives in this region
- The implementation of these proposed measures is expected to generate considerable economic benefits for the region by optimizing water resource management, improving agricultural efficiency, and supporting the development of hydroelectric energy systems [9]

In order to optimize the utilization of the river's water resources, the construction of the "Bakhtiyarli" reservoir is proposed, located above the city of Gubadli at an elevation of 540 meters above sea level. Based on preliminary hydrological reports, it is planned that up to 250.0 million cubic meters of the total water resources of the Bargushad River will be stored and preserved in the river channel below the newly constructed "Bakhtiyarli" reservoir. This water will be utilized for ecosystem conservation and local use.

The proposed reservoirs will be instrumental in enhancing the water quality for the aquatic species residing within this region. By regulating hydrological flow and mitigating sedimentation, these reservoirs are expected to contribute significantly to the stabilization of the aquatic ecosystem. Such interventions will facilitate the creation of a more conducive environment for aquatic life, characterized by optimized oxygen levels, diminished pollutant concentrations, and the enhancement of habitats essential for the survival and proliferation of fish populations. Furthermore, the sustained regulation of water flow and quality will foster biodiversity preservation and bolster the overall ecological health of the aquatic system, thereby supporting both fish communities and the broader surrounding ecosystem [14].

The Hakari River, with a length of 113 km and a catchment area of 2570 km², originates from the southern slope of the Mixtoken mountain range at an elevation of 2580 meters. It meets the Bargushad River near Qaralar village in Gubadli district (at an elevation of 340 meters above sea level), forming the Bazar River. At the confluence with the Bazar River, the annual water resource of the Hakari River is estimated at 500.0 million cubic meters. The average annual flow rate of the river is estimated to be 10.2 $m^3$/s. The primary water resource (up to 300.0 million cubic meters) of the river originates from the confluence of the Shalva and Hojazsu Rivers at an elevation of 950 meters. [10]

To enhance the efficient use of the river's water resources, it is deemed appropriate to utilize the annual flow volume (approximately 270.0 million cubic meters) formed at the confluence of the Shalva and Hojazsu Rivers within the country's boundaries for public water supply. To achieve this, the construction of a "Hakari" reservoir with a volume of 70.0 million cubic meters is proposed at this location.

As we know, the level of pollution in the Okhchu River has caused contamination in the Khudafarin reservoir, resulting in the mass mortality of fish. Therefore, to protect biodiversity and enhance fish stocks in the cleaner waters of the Hakari and Bargushad rivers, it is advisable to regulate the flow of water from these rivers towards the Khudafarin reservoir. To this end, the construction of a "Hakari-Bargushad" reservoir with a total volume of 60-70 million cubic meters at the confluence of these rivers at 340 meters above sea level is considered ecologically acceptable. This new reservoir will provide favorable conditions for the increase of indigenous fish species and will also allow for the use of part of the water accumulated throughout the year for irrigation purposes. The Master Plan for the utilization of water resources from the Bargushad and Hakari rivers for the development of fisheries is presented in Figure 3 [9].

The development of an aquaculture facility is envisioned within the reservoir to be constructed at the confluence of the Hakari and Bargushad Rivers. This facility will be integrated with the Khudafarin Reservoir through a fish migration infrastructure designed to facilitate the movement of aquatic species. The planned infrastructure will enable the annual transfer of up to 60-70 million cubic meters of water from the newly established reservoir to the Khudafarin Reservoir, thereby promoting the natural migration patterns of fish species. [4].

This integrated system will serve as a critical tool for preserving and enhancing the biodiversity of the Hakari and Bargushad river ecosystems. Moreover, it will play a pivotal role in mitigating the adverse effects of the highly polluted waters from the Okhchu River, which has been linked to significant fish mortality events in the Khudafarin Reservoir. By incorporating this infrastructure, the contamination risks associated with the inflow of polluted waters into the Hakari and Bargushad Rivers will be effectively managed, ensuring the long-term ecological stability and vitality of these aquatic ecosystems [18].

## 6. CONCLUSION

The following conclusions were obtained from the solution of the problem under study:

1. Systematic hydrochemical and ecotoxicological monitoring of the Okhchu, Bargushad, and Hakari rivers confirms the presence of distinct pollution regimes, ranging from severe contamination (Okhchu) to moderate, seasonally variable pollution (Bargushad) and relatively stable, low-contamination conditions (Hakari).
2. The Okhchu River is identified as a critical pollution source, with ammonium and heavy metal concentrations (Mn, Fe, Ni, Mo, Zn) exceeding permissible limits by up to 4.5-5.5 times, leading to unstable dissolved oxygen levels and documented mass fish mortality events. These

conditions render the river unsuitable for direct ecological or economic utilization without prior isolation or treatment.

3. The Bargushad River exhibits predictable seasonal fluctuations in heavy metal concentrations, particularly for iron, manganese, chromium, and lead. Although exceedances occur, the temporal regularity of contamination indicates that engineering regulation through reservoirs and sedimentation zones can significantly mitigate ecological risks.

4. The Hakari River demonstrates favorable water quality characteristics, with most physicochemical and heavy metal parameters remaining within WHO and EPA guideline limits. Low COD and $BOD_5$ values confirm its suitability for aquatic ecosystems, fish hatchery development, and sustainable aquaculture operations.

5. Comparative analysis proves that direct hydraulic integration of the polluted Okhchu River into downstream reservoirs poses a serious environmental risk, particularly to the Khudafarin Reservoir, necessitating strict flow regulation, isolation measures, or controlled diversion strategies.

6. The proposed Hakari-Bargushad reservoir system provides an effective engineering solution for pollution buffering, heavy metal sedimentation, and stabilization of water quality parameters, thereby reducing downstream contamination and enhancing ecological resilience.

7. Reservoir-based flow regulation enables the restoration of degraded fish habitats, improves spawning and juvenile survival conditions, and supports the recovery of endangered and native fish species affected by long-term pollution and hydrological disturbances.

8. The integration of fish hatcheries, breeding zones, and engineered migration corridors within the reservoir infrastructure ensures ecological connectivity while preventing exposure of sensitive species to polluted inflows.

9. From an engineering perspective, the multipurpose utilization of the reservoir system supports hydropower generation, irrigation supply, fisheries development, and biodiversity conservation, ensuring that renewable energy production aligns with environmental sustainability requirements.

10. The findings of this study provide a scientifically justified framework for integrated river basin management, offering practical guidance for environmental authorities and infrastructure planners to protect water resources, restore aquatic ecosystems, and promote sustainable socio-economic development in the region

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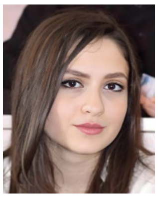

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