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Impact of Industrial Waste on Aquatic Ecosystems: A Case Study of the Okchu River

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Abstract

This study investigates the environmental impact of industrial pollution on the Okchu River, a critical water resource in the South Caucasus region. Originating from Kapicik Mountain and spanning 83 kilometers through Armenia and Azerbaijan, the river has been heavily polluted by copper-molybdenum mining activities near Gafan and Gajaran, Armenia. The research aims to assess the extent of heavy metal contamination, particularly copper, iron, and nickel, and its ecological implications on the river's fauna and groundwater quality.

Key findings reveal that concentrations of copper-molybdenum compounds in the river exceed permissible limits, posing significant health risks to local populations dependent on the river for water supply and irrigation. The study utilizes historical and recent data, including water and sediment analyses, to illustrate the worsening ecological condition of the Okchu River. Environmental monitoring conducted by both Azerbaijani and international agencies highlights the urgent need for remedial actions to mitigate further deterioration and protect the region's fragile ecosystems.

Despite its substantial hydropower potential, estimated at 130 million kWh annually, the Okchu River is now among the world's most polluted rivers, unfit for human use without extensive treatment. This study underscores the necessity for cross-border cooperation and sustainable management practices to restore and preserve the ecological integrity of the Okchu River basin. **Keywords:** channel, chemical parameters of water, ecosystem, hydropower, water resources

Introduction

The Okchu River originates from Kapicik Mountain (3,285 meters) in the Zangezur range. It enters the territory of our republic at an elevation of 630 meters and, after a 30-

kilometer course, flows into the Araz River at an elevation of 300 meters (Mammadov et al. 2023). The cities of Gafan and Gajaran, which host the main industrial areas of Armenia, are situated along its banks. Similarly, the city of Zangilan and the settlement of Minjivan in Azerbaijan are also located along this river (Hajiyeva 2022; Mirza 2023).

The river has an annual hydropower potential of 130 million kWh. However, this significant water resource has been polluted for many years by industrial waste from the copper-molybdenum mines near Gafan and Gajaran in Armenia (Chaturvedi et al. 2021). The pollution levels have exceeded all norms, resulting in the complete destruction of the river's fauna. Currently, the Okchu River is listed among the most polluted rivers in the world (Gasanov 2020; Godines-Madrigal et al. 2020; Shemer et al. 2023).

Using its water for supply and irrigation poses serious health risks. Recently, both Azerbaijani and Armenian media have reported that Armenia continues to discharge industrial waste into the Okchu River without any preliminary treatment (Gasanov and Makhmudov 2010; Mirza et al. 2021). According to a report by the Ministry of Ecology and Natural Resources of Azerbaijan, the levels of copper-molybdenum compounds in the water are twice the permissible limit, iron levels are four times higher, and nickel levels are seven times higher. Water samples taken from the Okchu River indicate a serious environmental threat, with the water occasionally appearing white or yellowish (Grison et al. 2023).

In 2017, experts from the Siberian Branch of the Russian Academy of Sciences determined that the water quality of the Okchu River corresponds to the IV degree of ecological condition for water basins located in the mining regions of the Syunik region. The influx of river water contaminated with heavy metals into our republic has created an ecological disaster (Rustamov and Kashkai 1989; Bertule et al. 2018). The Okchu River is considered one of the primary sources of groundwater recharge in the Zangilan region. The deposition of heavy metals along the river channel and their gradual mixing with groundwater is inevitable. Urgent measures are required to protect the existing ecosystem of the river channel and the valuable groundwater resources.

Materials and Methods

The Okchu River originates from Kapicik Mountain (3,285 meters) in the Zangezur range and enters the Republic of Azerbaijan at an elevation of 630 meters. It flows approximately 30 kilometers before joining the Araz River at an elevation of 300 meters. The river basin covers an area of 1,175 km^2 and is critical for the hydrological and ecological balance of the region. Water samples were collected from various points along the Okchu River, focusing on areas influenced by industrial activities and transboundary pollution from Armenia. Sampling was conducted monthly from January to March 2021 to assess seasonal variations and contamination levels. Samples were analyzed for concentrations of heavy metals (copper, molybdenum, manganese, iron, nickel, cadmium) using standard analytical techniques. The analyses included measurements of dissolved oxygen, biochemical oxygen demand (BOD_5), and nutrient levels (ammonium, nitrite). Bottom sediment samples were collected to evaluate the accumulation of heavy metals (chromium, manganese, iron, copper, nickel, cadmium, lead, zinc, molybdenum, cobalt). Sediment samples were taken in February 2021 to assess the deposition and persistence of pollutants. Long-term hydrological data from the Okchu River were analyzed statistically to determine flow rates and seasonal variations. Statistical methods included the calculation of average monthly water consumption and flow rates using historical data from the Okchuchay-Gafan hydrological station. The collected data were interpreted to assess the ecological impact of pollution on the Okchu River ecosystem. This included evaluating exceedances of permissible limits for heavy metals and their potential effects on aquatic life and human health. Comparative analysis was conducted with historical data from previous monitoring periods (1980-1989) to identify trends in water quality degradation and changes in pollutant concentrations over time.

Risk assessments were performed based on observed pollutant levels to quantify environmental risks associated with water and sediment contamination in the Okchu River. To mitigate the environmental impact of reduced water quality, strategies for ecological flow management were proposed. These strategies included the creation of reservoirs for storing relatively clean water and implementing controlled releases to maintain minimum flow rates necessary for ecosystem health. Experimental protocols adhered to international standards and guidelines for water quality monitoring and environmental sampling. Quality assurance and quality control measures were implemented throughout the sampling and analysis process to ensure data accuracy and reliability.

Results and Discussion

The Oxchu River is 83 km long with a catchment area of 1,175 km². It originates from Kapicic Mountain (3,285 meters) in the Zangezur range (Sakal 2022). The river enters our republic at an elevation of 630 meters and, after 30 km, merges with the Araz River at an elevation of 300 meters (Jianhua et al. 2016). It has been subjected to severe pollution within Armenian territory.

Hydrological observations of the river, which is unsuitable for water supply, were conducted from 1946 to 1988 in the Gafan district of Armenia. The river's average annual discharge is 11.2 cubic meters per second, with an annual volume of 353.7 million cubic meters. The river is primarily fed by snow (46%), rain (10%), and groundwater (44%). Seasonal distribution of its annual flow shows that 43% occurs in summer and 40% in spring (Hasanov and Zamanov, 1973; Hemmati et al. 2023).

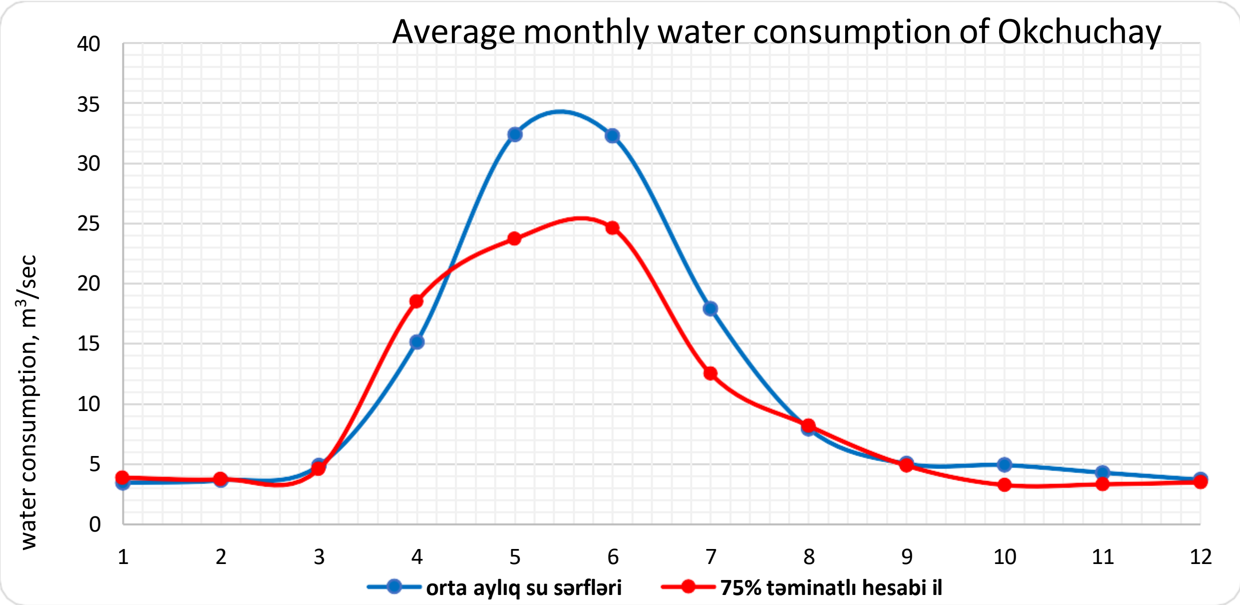
Based on the long-term observational data from the Okchuchay - Gafan hydrological station, statistical analyses were conducted. Tables and graphs illustrating the distribution and supply curves were subsequently constructed (Figure 1 and Table 1).

Table 1. Multi-year average monthly water consumption for Okchuchay-Gafan district (F = 643 km²)

Years	Average monthly water consumption, m³/san												
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Average annual
1965	3,48	3,71	4,90	10,7	26,7	32,8	24,4	6,61	4,25	6,33	5,42	3,93	11,1
1966	3,68	4,32	5,43	11,2	24,1	32,3	13,6	6,26	5,78	6,84	4,62	4,08	10,2
1967	5,11	5,51	6,34	15,9	50,8	32,3	21,3	10,3	5,46	6,05	6,62	6,21	14,4
1968	4,78	5,27	7,07	21,8	32,7	42,8	26,1	13,7	7,03	5,71	5,17	4,69	14,7
1969	3,94	4,20	5,98	20,5	40,8	39,5	21,7	10,7	5,87	7,79	6,64	5,42	14,4
1970	3,88	3,75	4,57	18,5	23,7	24,6	12,5	8,19	4,88	3,27	3,33	3,49	9,56
1971	2,67	1,71	2,14	6,30	18,1	18,3	10,0	3,98	2,19	1,72	1,82	1,74	5,89
1972	2,37	3,45	3,38	12,2	22,7	32,4	17,8	8,36	4,46	3,52	3,83	3,24	9,89
1973	3,55	3,57	4,92	14,5	35,9	41,9	21,4	9,19	5,02	3,76	4,03	2,54	12,6
1974	2,40	2,88	5,39	17,2	41,8	27,0	17,8	5,89	6,89	4,41	3,02	2,68	11,4
1975	2,24	1,90	3,45	17,8	38,8	30,6	10,5	4,21	3,57	4,81	2,79	2,73	10,3
Average	3,46	3,66	4,87	15,15	32,37	32,23	17,92	7,94	5,04	4,93	4,30	3,70	11,31

Collateral interest P %	1	2	5	10	20	25	30	40	50	60	70	75	80	90	95	97	99
Water consumption, $Q_{p\%}$ m³/san	17,19	16,40	15,27	14,25	13,12	12,78	12,33	11,76	11,20	10,63	10,07	9,73	9,39	8,48	7,92	7,46	6,67

Figure 1. Average monthly water consumption of Okchuchay



In the basin of the Okchu River, a left tributary of the Araz River, lie the industrial cities of Gafan and Gajaran, which are central to Armenia's mining industry. This river, a significant water resource for the region, has been polluted for many years by waste from the Gajaran copper-molybdenum and Gafan ore processing plants in Armenia (Solgi and Sheikzadeh 2016). The discharge of heavy metals (copper, molybdenum, manganese, iron, zinc, and chromium) into the Okchu River has not only destroyed its fauna and ecosystem but also poses a significant threat to human health (Nour et al. 2024; Pei et al. 2022; Seddon et al. 2020).

Monitoring by the Ministry of Ecology and Natural Resources of the Republic of Azerbaijan revealed that the concentrations of copper-molybdenum compounds in the water are twice the acceptable levels, iron is four times higher, and nickel is seven times higher (Salmanov et al. 2020). Water samples taken from the Okchuchay between January and March 2021 showed elevated levels of heavy metal pollution, with the water occasionally appearing white and dark yellow (Mehdiyeva et al. 2023).

Surface water monitoring in the Zangilan region was conducted according to relevant guidelines from the late 1970s until 1989. These monitoring efforts confirmed high levels of pollution in the transboundary rivers flowing through the region, including heavy metals, biogenic substances, and phenols (Sener et al. 2023; Tokajian and Hashwa 2003).

According to the results of monitoring conducted on the Okchuchay River in 2021, the concentrations of heavy metals and biogenic substances exceeded the normative levels. Specifically, the samples taken from the border post with Armenia showed elevated concentrations: ammonium at 1.6 times, manganese at 4.0 times, iron at 4.5 times, nickel at 5.5 times, cadmium at 2.9 times, and molybdenum at 1.9 times the acceptable limits (Tables 2-4).

a) b)

Figure 2. a) Photo of the Okchu River when it was dirty;

b) Mass destruction of fish in the Khudafar reservoir due to toxic water entering from Okchu River**.**

In a water sample taken approximately 5 km downstream from the upstream of Okchuchay, near the city of Zangilan, the concentrations of these components were found to be: ammonium 1.3 times higher than the norm (lower than the upstream levels), manganese 3.6 times higher, and nickel 3.4 times higher (Zhu et al. 2024).

At the beginning of March 2021, a large discharge of wastewater into the river resulted in a massive fish die-off (Figure 2).

Physico-chemical analyses of bottom sediment samples taken from the Okchuchay River identified the presence of heavy metals, including zinc, cobalt, lead, nickel, chromium, molybdenum, cadmium, copper, iron, and manganese (Li et al. 2021). Monitoring soil samples from the Zangilan region revealed that these soils are nutrient-rich and high in humus content. All ion content indicators were within acceptable norms, and the soils were characterized by higher cohesion and moisture capacity (Manafova 2019). Among the heavy metals, copper was found at slightly elevated levels in the soil samples, likely due to the natural occurrence of copper in the region's soils (Demir 2021).

Given the extreme pollution of the Okchuchay River, which ranks among the most polluted rivers globally, its water is unsuitable for supply and irrigation purposes. Therefore, it is more economically and ecologically viable to utilize only the river's hydropower potential, which is estimated at 110 million kWh annually.

Table 2. Results of collected bottom sediments (source: ETSN)

№	Assignable components	Unit of measurement	05.02.2021 Bottom sediment taken from Okchuchay river	Permissible Solidity Limit
1	Chrome, Cr	mg/kg	1,48	6,0
2	Manganese Mn	mg/kg	119,28	1500
3	Iron, Fe	mg/kg	278,88	37000
4	Copper, Cu	mg/kg	4,41	3,0
5	Nickel, Ni	mg/kg	0,56	4,0
6	Cadmium Cd	mg/kg	1,41	1,0
7	Lead Pb	mg/kg	1,29	32,0
8	Zinc, Zn	mg/kg	215,27	23,0
9	Molybdenum, Mo	mg/kg	0,289	10,5
10	Cobalt, Co	mg/kg	1,85	5,0

Table 3. Monitoring results conducted in Okchuchay in 1980-1989

№	Prescribed components	Unit of measurement	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
1	Dependents	mg/l	560	425	325	256	1940	870	525	521	756	157
2	Dissolved oxygen	mgO2/l	8,21	7,93	6,49	5,89	9,02	6,23	7,22	6,93	7,63	10,19
3	Biochemical consumption of oxygen, OBS_5	mg/l	1,06	1,21	1,19	1,24	1,23	1,65	1,31	0,99	1,39	1,23
4	Ammonium ion, NH_4+	mg/l	0,07	0,06	0,07	0,05	0,09	0,02	0,06	0,05	0,07	0,17
5	Nitrite ion, NO_{2-}	mg/l	0,03	0,009	0,03	0,02	0,004	0,007	0,009	0,031	0,015	0,06
6	Nitrate ion, NO_{3-}	mg/l	0,003	0,008	0,009	0,007	0,008	0,003	0,004	0,005	0,003	0,005
7	Zinc ion, Zn^{2+}	mg/l	0,69	0,25	0,45	0,39	0,59	0,64	0,21	0,56	0,34	1,97
8	Copper ion, Cu^{2+}	mg/l	0,001	0,007	0,005	0,004	0,009	0,002	0,006	0,004	0,003	0,008
9	Oil products	mg/l	0,01	0,03	0,02	0,03	0,03	0,03	0,06	0,004	0,02	0,05
10	Synthetic surfactants, SSAM	mg/l	0,044	0,053	0,063	0,078	0,038	0,045	0,078	0,046	0,068	0,027
11	Phenol	mg/l	0,002	0,003	0,001	0,015	0,003	0,002	0,001 5	0,004	0,003	0,019
12	Aluminum, Al	mg/l	0,006	0,0019	0,005	0,007	0,007	0,005	0,004	0,007	0,005	0,01

13	Manganese, Mn	mg/l	0,005	0,032	0,045	0,029	0,004	0,001	0,003	0,002	0,001	0,011
14	Titanium, Ti	mg/l	0,003	0,004	0,002	0,004	0,005	0,003	0,004	0,006	0,003	0,011
15	Total phosphate, PO_4^{3-}	mg/l	0,054	0,025	0,048	0,026	0,061	0,075	0,056	0,089	0,034	0,83

In 2023, the Ministry of Ecology and Natural Resources conducted regular monitoring of the Okchuchay River, which flows through the Zangilan district. A total of 108 water samples were collected, and 1,728 relevant physico-chemical analyses were conducted, covering the upper, middle, and lower reaches of the river. To assess pollution levels, 39 bottom sediment samples were taken throughout the year, and 398 physico-chemical and 3 ecotoxicological analyses were performed to determine heavy metal concentrations.

The results indicated that the levels of zinc, iron, manganese, and copper were higher than those of other metals. In the Shayifli district, closer to the Armenian border, 36 water samples were collected, and 576 physico-chemical analyses were performed. Analysis results showed that the water content varied between 1.1 and 2.4 times the permissible limits, with the highest concentrations recorded in the first decade of February and the lowest in the first decade of August.

Sulfate ion (SO_4) levels in late January were found to be 1.2 times higher than the permissible concentration limit. Ammonium ion (NH_4) levels varied between 2.2 and 4.8 times the acceptable limit, peaking in late February and reaching their lowest in late November. Iron (Fe) concentrations ranged from 1.3 to 6.8 times the permissible limit, with the highest levels in early May and the lowest in mid-January. Manganese (Mn) concentrations varied from 1.1 to 6.7 times the acceptable limit, peaking in late February and dipping in mid-July. Molybdenum (Mo) levels ranged from 1.1 to 2.7 times the permissible limit, with the highest concentrations in late February and the lowest in early September (Figure 3).

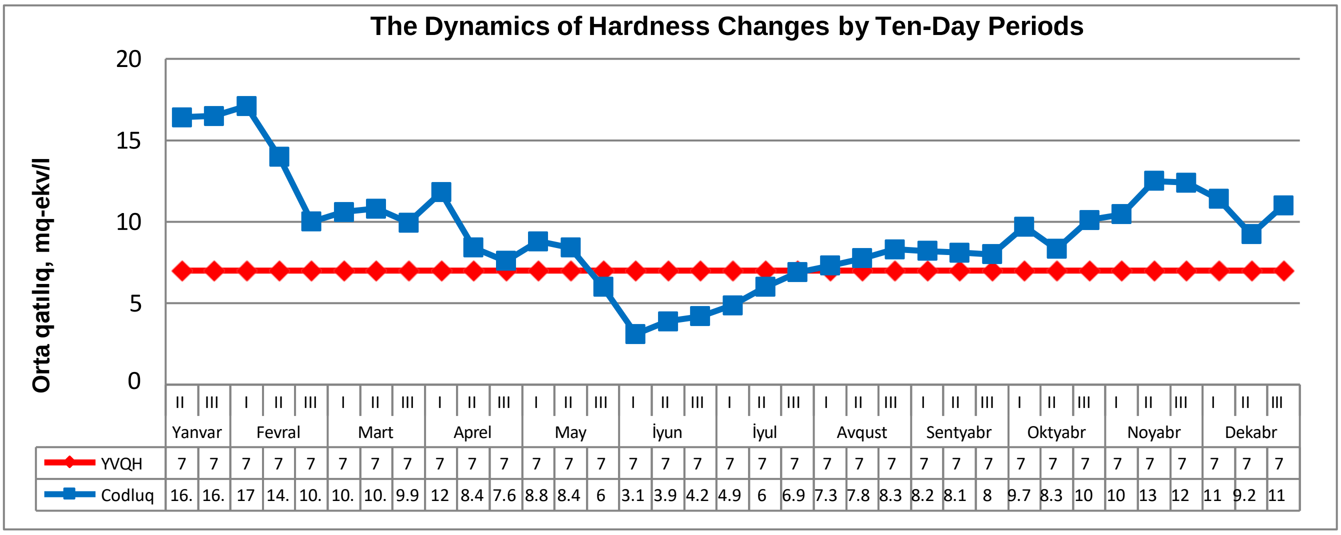
The Okchu River has suffered extensive heavy metal pollution, resulting in the complete destruction of its valuable fish population. Numerous reports have documented severe fish mortality in the Khudafar reservoir, attributed to recurrent high levels of river pollution originating from Armenian territory. Research conducted by ichthyologists from the Islamic Republic of Iran at the Khudafar reservoir has identified toxic water inflow from the Okchu River as the primary cause of the mass fish deaths (Doustdar et al. 2016; Al-Mefleh et al. 2019).

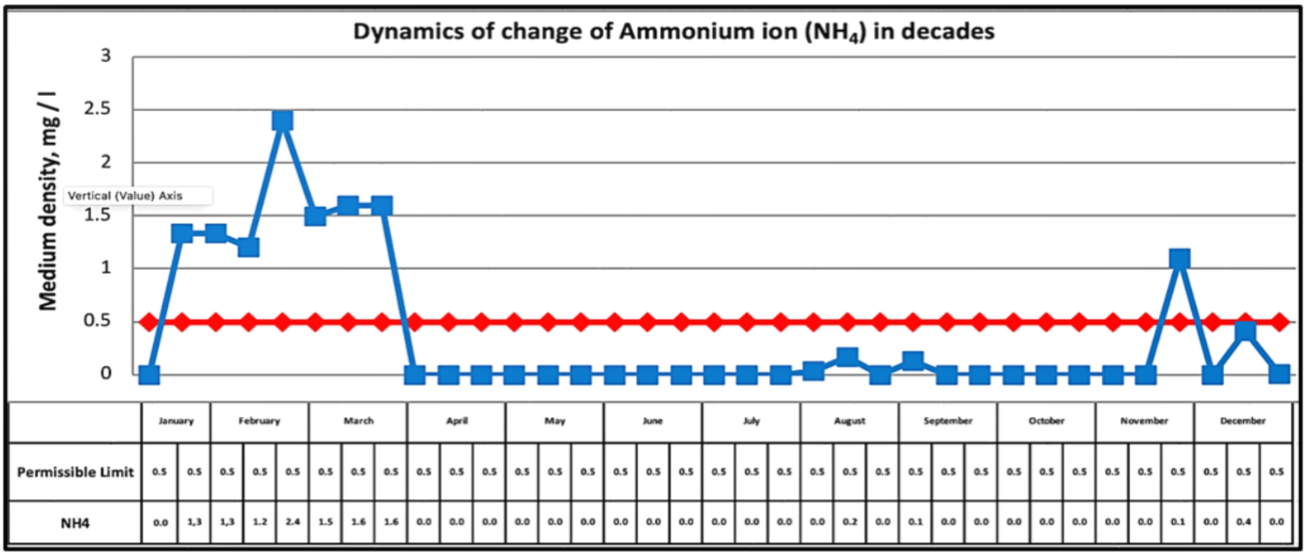
Table 4. Monitoring data on average monthly indicators of Okchuchay in 2021 (source: ETSN)

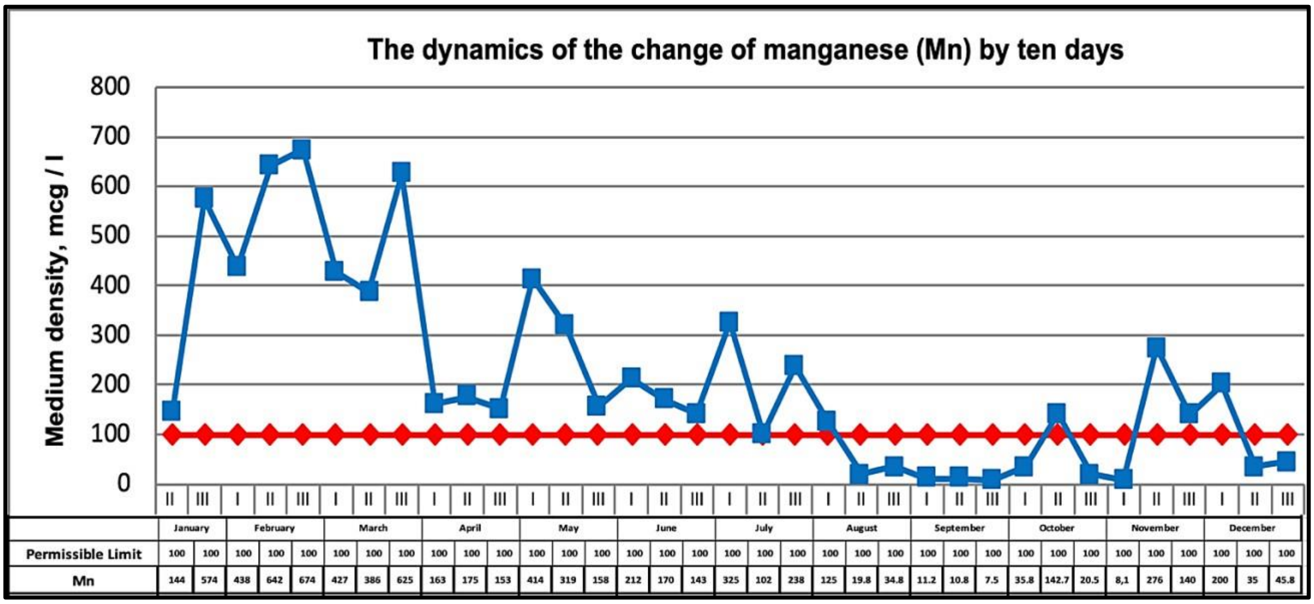
№	The name of the component	Unit of measurement	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	PCL
1	Hydrogen indicator, pH	—	7,20	7,37	7,66	7,84	7,65	7,64	7,75	7,15	7,79	6,74	8,03	7,57	***6,5-8,5***
2	Dissolved oxygen	mgO_2/L	5,78	7,43	-	6,90	6,65	6,86	5,93	6,02	6,40	7,05	8,36	8,93	***≥4,0***
		%	59,56	73,10	-	73,12	73,83	73,35	71,78	72,33	76,81	76,25	87,75	92,66	
3	Electrical conductivity	x10-3 cm/cm	0,74	0,61	0,51	0,36	0,28	0,36	0,52	0,56	1,00	1,09	0,87	0,77	—
4	Hardness	mg-eq/l	4,99	4,62	-	2,98	2,63	3,05	3,81	4,76	**9,53**	**11,24**	**10,98**	8,05	***7,0***
5	Calcium ion, Ca^{2+}	mg/l	74,78	67,24	-	41,36	35,41	42,71	53,43	66,74	133,63	157,68	154,05	112,99	–
6	Magnesium ion, Mg^{2+}	mg/l	15,45	17,37	-	11,08	10,51	11,00	13,90	17,35	34,74	41,00	40,06	29,36	–
7	Chloride ion, Cl^-	mg/l	22,84	52,80	-	20,44	9,66	9,02	9,96	11,67	18,46	15,59	16,45	16,83	***350***
8	Sulfate ion, SO_4^{2-}	mg/l	322,17	148,39	-	71,70	53,29	92,88	93,61	121,43	349,79	359,38	237,02	189,37	***500***
9	Hydrocarbonate ion, HCO_3^-	mg/l	81,78	197,97	-	120,90	114,04	124,22	217,62	213,77	299,92	382,25	269,93	232,37	-
10	Carbonate ion, CO_3^{2-}	mg/l	0,00	0,00	-	0,00	0,00	0,00	0,00	0,00	0,00	0,00	11,00	0,00	-
11	Na^++ K^+ ions	mg/l	81,53	-	-	23,45	10,50	-	0,00	-	-	-	0,00	0,00	-
12	Ammonium ion, NH_4^+	mg/l	0,58	0,06	0,30	0,14	0,13	0,06	0,02	0,00	0,11	0,27	0,50	**0,65**	***0,5***
13	Nitrite ion, NO_2-	mg/l	0,33	0,02	0,08	0,21	0,14	0,14	0,39	0,35	0,47	0,75	0,13	0,49	***3,3***
14	Nitrate ion, NO_3-	mg/l	6,44	2,24	2,78	4,63	2,42	2,93	3,52	2,76	2,23	2,82	2,97	3,71	***45,0***
15	Orthophosphate ion, PO_4^{3-}	mg/l	0,01	0,07	0,03	0,01	0,05	0,02	0,19	0,38	0,37	0,48	0,38	0,42	***3,5***
16	Sum of ions, ∑	mg/l	586,23	487,17	-	271,96	231,25	283,00	406,71	441,81	841,66	960,06	732,46	586,19	***<1000***
17	Chrome, Cr	mkg/l	68,50	19,43	0,00	0,00	0,00	-	1,47	1,24	1,05	2,99	2,49	1,56	***500***

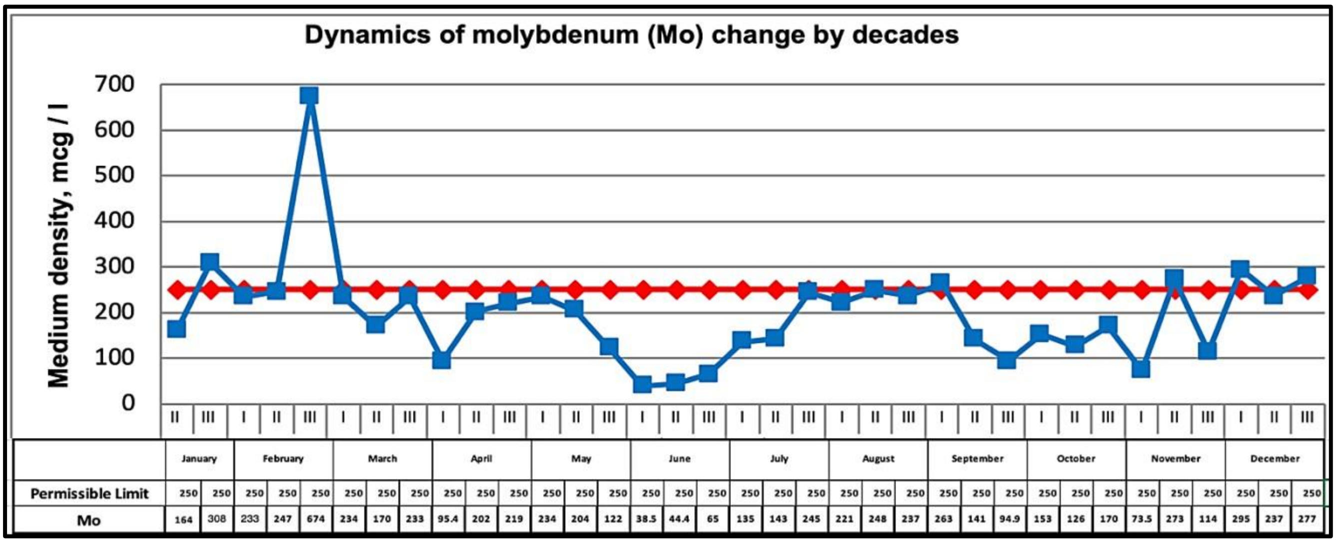
18	Mangan, Mn	mkg/l	**306,12**	**195,80**	**124,10**	58,80	**110,66**	52,08	90,46	**242,50**	**141,57**	241,81	75,27	**187,93**	*100*
19	Iron, Fe	mkg/l	**688,60**	**1299,14**	276,00	**541,20**	**755,38**	**306,08**	268,13	**492,00**	**581,30**	**1054,99**	**376,57**	**443,23**	*300*
20	Copper, Cu	µg/l	163,56	138,74	78,44	57,42	73,86	30,61	42,25	112,55	82,15	139,24	37,94	39,49	*1000*
21	Nickel, Ni	µg/l	**546,20**	155,50	1,03	1,68	2,89	3,19	3,50	-	1,77	2,94	2,71	1,10	*100*
22	Cadmium, Cd	µg/l	**2,43**	0,44	**1,82**	**1,47**	**1,76**	0,77	0,71	0,38	0,54	0,58	0,29	<LOD	*1*
23	Lead, Pb	µg/l	18,18	7,25	10,88	6,92	12,14	5,13	3,91	5,23	5,59	5,95	4,50	5,66	*30*
24	Zinc, Zn	µg/l	330,46	208,94	76,21	63,50	90,73	34,61	33,35	80,08	98,51	269,85	72,87	121,60	*1000*
25	Molybdenum, Mo	µg/l	**324,40**	**303,71**	68,92	54,57	30,96	63,85	131,13	186,30	179,02	134,36	203,78	**331,55**	*250*
26	Cobalt, Co	mkg/l	68,25	20,47	3,06	3,18	3,15	3,35	7,08	6,18	<LOD	0,42	3,65	<LOD	*100*

Figure 3. Dynamics of change of chlorine, ions (NH4, SO4) and heavy metals (Fe, Mn, Mo) in the water environment of Shayifli district of Okchuchay by ten days




Dynamics of change of Ammonium ion (NH4) in decades
Medium density, mg / l
Vertical (Value) Axis
3
2.5
2
1.5
1
0.5
0
January February March April May June July August September October November December
Permissible Limit 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5
NH4 0.0 1,3 1,3 1.2 2.4 1.5 1.6 1.6 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.2 0.0 0.1 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.1 0.0 0.4 0.0


The dynamics of the change of manganese (Mn) by ten days
Medium density, mcg / l
800
700
600
500
400
300
200
100
0
II III I II III I II III I II III I II III I II III I II III I II III I II III I II III I II III I II III
January February March April May June July August September October November December
Permissible Limit 100 100 100 100 100 100 100 100 100 100 100 100 100 100 100 100 100 100 100 100 100 100 100 100 100 100 100 100 100 100 100 100 100 100 100
Mn 144 574 438 642 674 427 386 625 163 175 153 414 319 158 212 170 143 325 102 238 125 19.8 34.8 11.2 10.8 7.5 35.8 142.7 20.5 8,1 276 140 200 35 45.8


Dynamics of molybdenum (Mo) change by decades
Medium density, mcg / l
700
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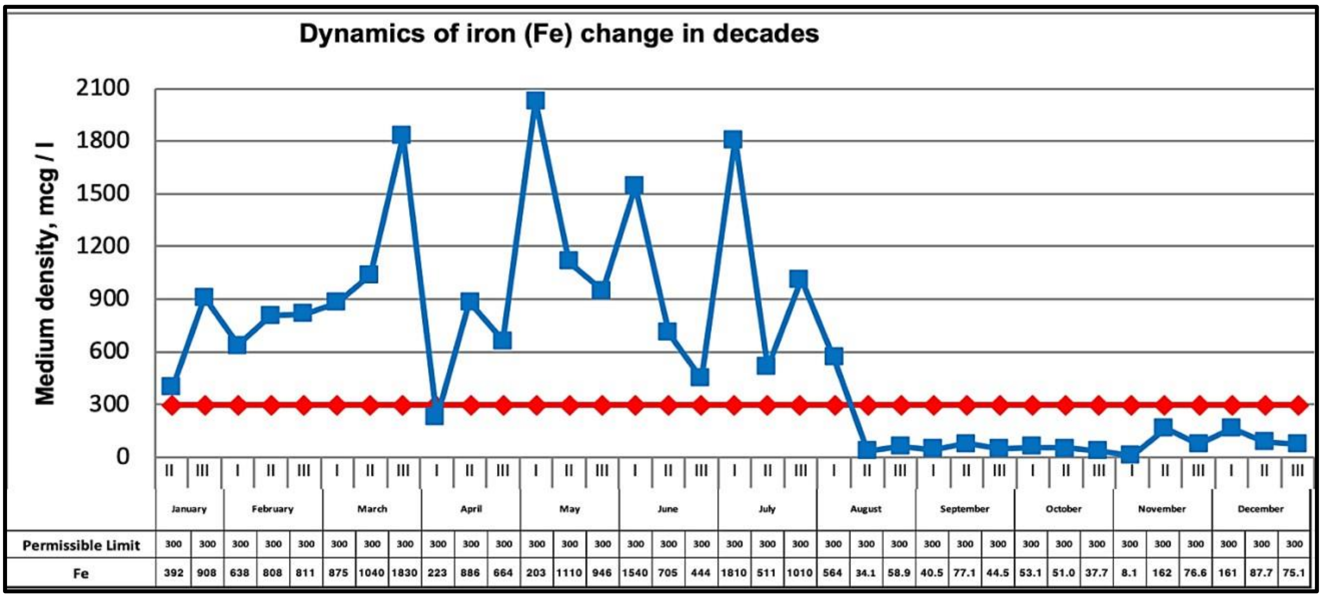

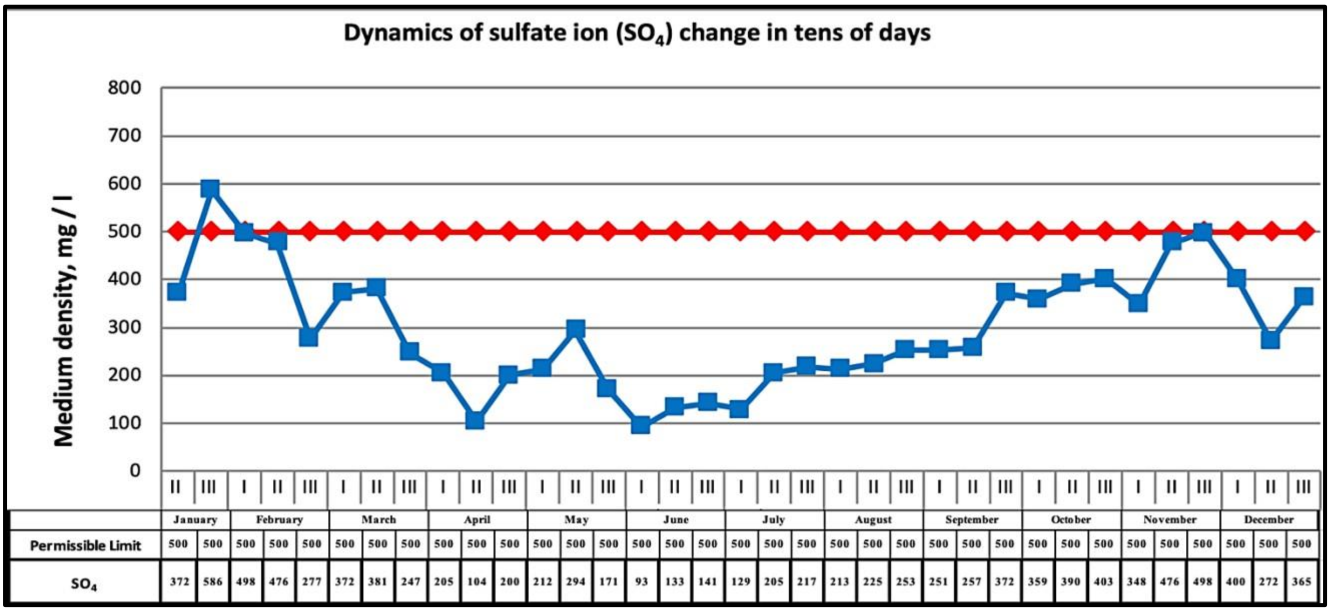

Effective Utilization of Okchuchai River's Hydropower Potential: The dual objectives of protecting the Okchuchai River ecosystem and harnessing its hydropower potential can be addressed through a unified project. As depicted in Figure 2, the concentration of heavy metals in the river water fluctuates seasonally and generally falls below permissible limits from August to November (based on 2023 data).

To facilitate continuous monitoring of water quality indicators, specialized automated monitoring equipment should be installed in the river's entry point into our republic. As part of this initiative, a regulating reservoir with a capacity of 3-4 million cubic meters should be constructed at the 630-meter elevation where the river enters our territory. Water collected in this reservoir will be diverted from the main channel via a DN2200 mm derivation pipe spanning 13.0 km. It will then be conveyed to the "Zangilan-1" Hydropower Plant (HPP), planned near Zangilan city at 465 meters elevation, with a total installed capacity of 9.5 MW.

These HPPs are projected to generate approximately 120-140 million kWh of electricity annually. Both HPPs will utilize turbines designed for a 150 m head pressure (Ref. 5).

Initially, the river water from the hydropower plant (HPP) will be conveyed to the "Zangilan-2" HPP, to be constructed at an elevation of 300 meters along the Araz River, through a DN 2200 mm diameter pipe spanning a length of 17.0 km.

It will be possible to generate 70 million kWh of electricity annually through this Small Hydropower Plant (SHP) (Figure 4). By utilizing the electricity generated from both SHPs, it is feasible to provide uninterrupted 'Green Energy' to more than 90,000 people.

The SHPs will primarily operate in river overflow mode during the months of April to July, with a water discharge of 18-20 m^3/sec. According to foundational data (Table 1), only 10 m^3/sec of flow will be diverted into the intake pipes in May and June due to limitations. Throughout the other ten months, the entire river flow can be redirected into the Araz River via the SHPs, enhancing the river's water quality. Transporting more polluted water out of the channel in transit mode will greatly benefit the protection of the river channel's ecosystem.

During periods of relatively clean river flow, a portion of the water collected in the intake-reservoir will be directed via a 5.3 km long DN 1600 mm pipeline to the 'Shayifli' reservoir, located outside the channel. The purified water stored in this reservoir will be reintroduced into the river as an ecological flow. This approach using resources from the newly constructed 'Shayifli' reservoir will create extensive technical capabilities for safeguarding the Okchu River's ecosystem. The influx of predominantly clean water into the river channel is crucial for protecting underground water sources (Khiyat 2022).

Implementing this project as planned could significantly alleviate the ecological disaster along the river's course and yield a substantial amount of electricity (Rashidi et al. 2021). Currently, construction is underway for 4 SHPs harnessing the hydropower potential of Okchuchay (Pashayev and Gasanov 2017).

The following measures are proposed for the protection of the ecosystem along the Okchu River's course:

- Installation of specialized automatic equipment at the river's entry point into the republic's territory to monitor water quality indicators.
- Establishment of an intake-reservoir at the river's entry point into the republic to enable daily regulation of its flow regime.
- Direction of inflow to the reservoir based on water quality indicators upon intake.

- Diversion of highly polluted flows from the river channel to the Araz River via Hydroelectric Power Stations through a diversion pipeline.
- Collection of clean river water in a reservoir outside the channel on the right bank of the Shayifli branch during periods of pollution levels below standard.
- Construction of the 'Shayifli' reservoir with a capacity of up to 35 million cubic meters on the Shayifli tributary, covering a catchment area of 28.4 km², to maintain ecological flow in the river.
- Installation of a 5.3 km long, DN 1600 mm diameter water pipeline to transport a portion of fresh water from the intake reservoir to the newly constructed 'Shayifli' water reservoir via natural flow.
- Utilization of all planned hydrotechnical systems to ensure an ecological flow regime of 1.5-2.0 m³/sec along the Okchu River's course.
- Implementation of a strategy to safeguard the river channel's ecosystem by releasing water from the clean water reserve stored in the Shayifli reservoir at a rate of 1.5-2.0 m³/sec. as ecological flow.

The catchment area of the 'Shayifli' reservoir, intended to preserve the ecological balance and ecosystem of the river, is predominantly forested. Annually, approximately 15.7 million cubic meters of clean rainwater is generated from this area. This rainwater will be collected in the newly constructed reservoir and utilized to maintain an ecological flow in the river. The overall layout of the proposed hydrotechnical facilities system is depicted in Figure 4.

Figure 4. Plan of facilities to be created for ecosystem protection in Okchu River

Integrated Hydropower and Ecosystem Protection Plan for the Okchu River:

- In the territory of the Republic of Armenia, urgent measures are necessary to protect the ecosystem along the 30 km stretch of the Okchu River, heavily contaminated with heavy metals.
- To maximize ecosystem protection within the river channel, it is proposed to develop hydropower plants (HPPs) totaling 40 MW capacity, diverting the primary river flow through a derivation pipe constructed alongside its channel.
- This approach to HPP development allows for optimal utilization of the river's hydropower potential, with 80-90% of the flow redirected and discharged into the Araz River.
- Installation of specialized river sensors can identify periods of relatively clean flow, enabling the collection of this water in an off-channel reservoir for subsequent release as ecological flow into the river channel.
- A reservoir with a capacity of 35 million cubic meters can be constructed on the Shayifli tributary's right bank, outside the river's main course.
- By filling the "Shayifli" reservoir during periods of cleaner water from the Okchu River, consistent regulation of ecological flow ($Qeko \approx 1.5\text{-}2.0$ m3/sec) can be maintained within the river's natural course.

Conclusion

The Okchu River, originating from the Kapicik Mountain in the Zangezur range, serves as a vital water resource in the region, but its severe pollution due to industrial waste has transformed it into one of the world's most polluted rivers. The discharge of untreated industrial effluents, particularly from copper-molybdenum mines in Armenia, has drastically degraded water quality, resulting in the complete destruction of its fauna and posing significant health risks to human populations relying on its water.

Monitoring efforts have consistently revealed elevated concentrations of heavy metals such as copper, molybdenum, iron, nickel, and manganese, far exceeding permissible limits. These pollutants not only contaminate surface water but also threaten groundwater quality in the Zangilan region, where the river plays a crucial role in groundwater recharge.

The ecological disaster unfolding in the Okchu River demands urgent action to protect its ecosystem and the health of local communities. Effective management strategies must be implemented to mitigate further pollution and restore the river's water quality. Furthermore, prioritizing the river's hydropower potential over its compromised water supply function appears both economically viable and ecologically sustainable in the face of current challenges.

Sustained collaborative efforts between Armenia and Azerbaijan are essential to address transboundary pollution issues effectively and ensure the sustainable management of this critical natural resource for future generations.

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