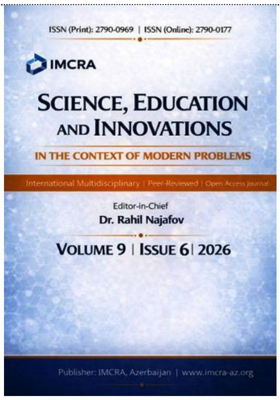

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RESEARCH ARTICLE

Environmental Risk Assessment of Manganese and Heavy Metal Contamination in the Kvirila River and Spring Waters of Chiatura Municipality

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Keywords Kvirila River; spring waters; manganese; heavy metals; environmental pollution; hazard quotient; risk assessment.

Abstract
Chiatura Municipality, located in the Imereti Region of Georgia, is one of the country's most environmentally vulnerable mining areas, where manganese ore has been extracted and processed since 1879. Intensive mining activities have exerted considerable environmental pressure on the Kvirila River, which is used for washing extracted ore. Consequently, untreated wastewater containing suspended solids, manganese compounds, and heavy metals is discharged directly into the river, contributing to water pollution. This study assessed the contamination risk of the Kvirila River and nearby spring waters located adjacent to manganese-processing enterprises in Chiatura Municipality during 2024–2025. The total concentrations of manganese (Mn) and selected heavy metals (Cu, Zn, Pb, Cd, Ni, and Co) were determined in river water, spring water, suspended solids, and bottom sediment samples. Environmental risk was evaluated using the Hazard Quotient (HQ) approach. All laboratory analyses were performed using modern analytical methods and equipment in accordance with European standards. The results showed that, with the exception of manganese, the concentrations of all analyzed heavy metals remained

below their corresponding maximum permissible concentrations (MPCs) in both background and polluted water samples. The Kvirila River and the investigated spring waters were classified as slightly to moderately mineralized. The manganese hazard quotient for the Kvirila River (HQ_{SW} > 1) indicates a potential environmental risk associated with manganese contamination, whereas the concentrations of the remaining heavy metals, although generally higher than background levels, did not exceed their respective MPCs. In contrast, the manganese hazard quotient for the spring waters (HQ_{DW} < 1) indicates that these waters do not pose a significant environmental or human health risk. Elevated manganese concentrations were also detected in suspended solids and bottom sediments from the Kvirila River, confirming the substantial impact of mining activities on the aquatic environment.

Citation

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1. INTRODUCTION

The continuous growth of the global population, rapid industrial development, and increasing anthropogenic pressure on the environment have significantly contributed to climate change.

The adverse effects of climate change on Georgia's ecosystems and economy pose a serious challenge to the country's sustainable development. Georgia's unique geographical location, complex mountainous terrain, diverse land cover, and climatic diversity create favorable conditions for the occurrence of a wide range of climate-related hazards. These characteristics also increase the country's vulnerability to the impacts of climate change.

The prevention and mitigation of climate-related disasters are therefore of critical importance, as such events affect multiple sectors, including public health, ecosystems, infrastructure, tourism, agriculture, and natural resources.

Within Georgia, Chiatura Municipality is considered one of the most environmentally vulnerable regions. Against the backdrop of climate change, the municipality has experienced an increased frequency of natural hazards, including landslides, mudflows, floods, strong winds, and soil erosion, which are further intensified by extensive manganese mining activities. Although ore extraction contributes to economic development through employment opportunities and income generation, it also has considerable adverse environmental and social consequences (Friends of the Earth Europe, 2007; Tsereteli et al., 2012). Mining activities may result in deforestation, destruction of vegetation cover, severe landscape degradation, biodiversity loss, ecosystem contamination, food pollution, soil degradation, and substantial economic losses (Friends of the Earth Europe, 2007).

Industrial wastewater generated during the ore-washing process contains large quantities of suspended solids, heavy metals, and manganese compounds, which are discharged directly into the Kvirila River without treatment. Furthermore, thousands of tons of agglomerate waste are stored at a landfill located on the left bank of the Kvirila River. This material contains an average manganese concentration of approximately 15.4%. Under the influence of precipitation, manganese-containing agglomerates are washed into the river, resulting in additional environmental contamination (LEPL Grigol Tsulukidze Mining Institute et al., 2010).

During manganese extraction and processing, manganese oxide is released into the atmosphere as airborne dust. Wind and precipitation facilitate its dispersion and subsequent deposition throughout the municipality, contributing to further environmental pollution (Liberali, 2018).

Manganese is an essential trace element for both humans and animals and is naturally present in low concentrations in most human organs. It plays an important role in hematopoiesis, bone formation, and the metabolism of proteins, carbohydrates, and lipids. In plants, manganese is an essential component of the photosynthetic process. However, both manganese deficiency and excessive exposure may have adverse health effects. Although manganese does not typically cause acute toxicity, it is considered a cumulative toxic element. Long-term exposure may result in chronic health disorders, including manganism, bronchial asthma, allergic dermatitis, and other occupational diseases (Ministry of Labor, Health and Social Protection of Georgia, 2007).

2. LITERATURE REVIEW

Mining activities represent one of the major sources of environmental contamination worldwide, particularly through the release of heavy metals into aquatic ecosystems. The extraction and processing of mineral resources frequently generate untreated wastewater, suspended solids, and contaminated sediments, leading to long-term degradation of surface water quality and increased ecological and human health risks (World Resources Institute, 2003). Environmental contamination associated with mining has become a growing concern because heavy metals persist in aquatic environments, accumulate in sediments, and may enter food chains, posing chronic risks to ecosystems and public health.

Georgia is particularly vulnerable to environmental degradation caused by intensive mining activities due to its complex mountainous terrain, diverse hydrographic network, and long history of mineral exploitation. Studies conducted in Georgia have highlighted that anthropogenic pressures combined with natural geomorphological processes significantly increase the country's susceptibility to environmental hazards, including water pollution, erosion, and ecosystem degradation (Tsereteli et al., 2012). Among the country's mining regions, Chiatura Municipality represents one of the most environmentally sensitive areas because manganese extraction has been continuously carried out since the nineteenth century.

Numerous reports have documented that mining operations generate substantial quantities of industrial wastewater containing suspended particles and dissolved metals that are often discharged into nearby rivers without adequate treatment. The environmental impacts of extractive industries extend beyond water pollution and include soil degradation, biodiversity loss, landscape destruction, and long-term ecological disturbances (Friends of the Earth Europe, 2007). In Chiatura, previous technical investigations have shown that waste generated during manganese processing contributes significantly to contamination of the Kvirila River through continuous runoff from waste disposal sites and ore washing facilities (LEPL Grigol Tsulukidze Mining Institute, 2010).

Manganese deserves particular attention because, although it is an essential trace element involved in numerous physiological processes in humans, animals, and plants, excessive exposure may cause cumulative toxic effects. Chronic manganese exposure has been associated with neurological disorders, respiratory diseases, and occupational illnesses among exposed populations (Order of the Minister of Labor, Health and Social Protection of Georgia, 2007). Consequently, continuous monitoring of manganese concentrations in surface waters and drinking water resources is essential for protecting environmental and public health.

Risk assessment has become an important component of modern environmental monitoring. Instead of simply comparing contaminant concentrations with regulatory limits, contemporary environmental studies increasingly employ hazard indices and ecological risk models to quantify potential impacts on ecosystems and human populations. The methodology developed by the Water Research Institute of the Slovak Republic (2019) provides an effective framework for evaluating heavy metal contamination by comparing measured concentrations with environmental quality standards through hazard quotient (HQ) calculations. This approach has been widely adopted in environmental monitoring because it allows direct interpretation of ecological risk.

Recent studies conducted in western Georgia have successfully applied similar analytical methodologies to evaluate contamination by arsenic and heavy metals in rivers and surrounding ecosystems. Shavliashvili et al. (2025) demonstrated the effectiveness of phytoremediation techniques for arsenic-contaminated soils in Ambrolauri Municipality, while Tabatadze et al. (2025) employed statistical analyses of hydrochemical parameters to characterize natural water quality in the Racha-Lechkhumi and Kvemo Svaneti regions. Furthermore, Shavliashvili et al. (2025) investigated the influence of arsenic industry waste on soil contamination, confirming that mining activities remain a significant source of environmental pollution in western Georgia.

Despite these important contributions, relatively few studies have comprehensively assessed manganese contamination simultaneously in river water, suspended solids, bottom sediments, and drinking water sources within the Chiatura mining region. Most previous investigations have focused either on individual environmental compartments or on general hydrochemical characteristics without integrating ecological risk assessment. Therefore, there remains a need for comprehensive monitoring that combines laboratory determination of manganese and heavy metal concentrations with internationally recognized hazard assessment methodologies.

The present study addresses this research gap by evaluating manganese and selected heavy metal contamination in the Kvirila River and nearby spring waters during 2024–2025 using standardized analytical methods and hazard index calculations. The findings provide updated evidence regarding the ecological status of one of Georgia's most important mining regions and contribute valuable information for environmental management, pollution mitigation, and sustainable water resource protection.

3. RESEARCH AREA AND METHODS

This study provides a physicochemical characterization of the waters of the Kvirila River in the areas surrounding the manganese processing plants of Chiatura Municipality. Assessing the quality of the Kvirila River is essential because its water is used for washing extracted manganese ore, after which untreated wastewater is discharged directly into the river, resulting in environmental pollution.

To achieve the objectives of the study, water samples were collected from both background locations and sites located downstream of the pollution sources along the Kvirila River. In addition, samples of suspended solids, bottom sediments, and spring water intended for drinking purposes were collected for analysis.

The collected water samples were analyzed for pH and the total concentrations of manganese (Mn) and selected heavy metals, including copper (Cu), zinc (Zn), lead (Pb), cadmium (Cd), nickel (Ni), and cobalt (Co) (Fomin & Fomin, 2001).

The risk assessment was performed by comparing the measured manganese (Mn) concentrations with the environmental quality standards established for surface water and drinking water. The hazard quotient (HQ) was calculated using the following equation (Water Research Institute of the Slovak Republic, 2019):

$$[HQ = \frac{MC}{EQS_{SW,DW}}]$$

where:

HQ = Hazard Quotient (Hazard Index);

MC = Measured concentration of manganese;

EQS_{SW,DW} = Environmental Quality Standard for surface water or drinking water.

An HQ value greater than 1.0 (HQ > 1) indicates that manganese may pose a potential environmental risk to the aquatic environment and, consequently, to human health.

The environmental quality standard (EQS) values adopted in this study were as follows:

- Surface water: 0.1 mg/L, according to Resolution No. 425 on the Technical Regulations for the Protection of Surface Waters of Georgia from Pollution (Government of Georgia, 2013).
- Drinking water: 0.4 mg/L, according to Resolution No. 58 on the Technical Regulations for Drinking Water (Government of Georgia, 2014).

All laboratory analyses were performed using modern analytical instruments that comply with European standards. The equipment employed in this study included:

- Inductively Coupled Plasma Optical Emission Spectrometer (ICP–OES), EPA Method 200.8;
- Hanna Combo pH/EC/TDS/PPM Tester (HI98129) for field measurements;
- Milwaukee MI150 pH Meter for laboratory pH determination.

4. RESULTS

Table 1 presents the concentrations of manganese and selected heavy metals in the Kvirila River and spring water samples collected during 2024 and 2025. For manganese, the numerator indicates the measured concentration (mg/L), while the denominator represents the corresponding multiple of the maximum permissible concentration (MPC).

As shown in Table 1, in May 2024 the pH values measured downstream of Andro LLC and Jruchula LLC ranged from 8.1 to 8.2, indicating a slight shift toward alkaline conditions compared with the background value of the Kvirila River (pH 7.7). The manganese concentration downstream of Andro LLC was 2.5649 mg/L, corresponding to 25.6 times the MPC, whereas downstream of Jruchula LLC it was 0.1136 mg/L, equivalent to 1.1 times the MPC. The elevated manganese concentration downstream of Andro LLC is attributed to the discharge of wastewater generated during ore washing into the Kvirila River. In contrast, the relatively low concentration downstream of Jruchula LLC suggests that the enterprise may not have been operating at full production capacity during the sampling period (Figure 1).

The manganese concentrations in both spring water samples remained within the permissible limits.

Among the analyzed heavy metals, only manganese exceeded the maximum permissible concentration. The concentrations of copper (Cu), zinc (Zn), lead (Pb), cadmium (Cd), nickel (Ni), and cobalt (Co) remained below the corresponding MPC values in all analyzed water samples (Table 1; Figure 1).

In November 2024, the manganese concentration in the Kvirila River reached 1.3958 mg/L (13.9× MPC) downstream of Andro LLC and 1.3742 mg/L (13.7× MPC) downstream of Jruchula LLC. Notably, the background concentration of manganese in the Kvirila River was also elevated, reaching 0.2572 mg/L, equivalent to 2.6 times the MPC. In contrast, the concentrations of all other analyzed heavy metals remained below their respective maximum permissible concentrations.

Table 1. Heavy metal concentrations in the waters of the Kvirila River and spring water, 2024, 2025

N	Ingredients	Kvirila-below "Andro" LLC	Kvirila-below "Jruchula" LLC	Kvirila-Background	Spring water 1	Spring water - 2	MPC *	MPC **
		May, 2024						
1	pH	8.1	8.2	7.7	8.2	7.8	6-9	6.5-8.5
2	Manganese, mg/l	2.5649/25.6	0.1136/1.1	0.0150	0.0154	0.0030	0.4	0.1
3	Copper, mg/l	0.0134	0.0024	0.0040	0.0028	0.0008	2.0	1.0
4	Zinc, mg/l	0.0054	0.0035	0.0012	0.0031	0.0009	3.0	1.0
5	Lead, mg/l	0.0023	0.0011	0.0008	0.0021	0.0015	0.01	0.03
6	Cadmium, mg/l	0.0002	0.0001	0.0001	<0.0001	<0.0001	0.003	0.001
7	Nickel, mg/l	0.0005	0.0023	0.0007	0.0010	0.0005	0.07	0.1
8	Cobalt, mg/l	0.0004	0.0007	0.0003	0.0012	0.0009		0.1
		November, 2024						
1	Manganese, mg/l	1.3958/13.9	1.3742/13.7	0.2572/2.6	0.0050		0.4	0.1
2	Copper, mg/l	0.0032	0.0038	0.0040	0.0010		2.0	1.0
3	Zinc, mg/l	0.0522	0.0456	0.0013	0.0008		3.0	1.0
4	Lead, mg/l	0.0012	0.0024	0.0009	0.0011		0.01	0.03
5	Cadmium, mg/l	0.0003	0.0004	<0.0001	<0.0001		0.003	0.001
6	Cobalt, mg/l	0.0011	0.0007	0.0005	0.0003			0.1
7	Nickel, mg/l	0.0023	0.0033	0.0015	0.0004		0.07	0.1
		June, 2025						
1	pH	7.9	8.0	8.1	8.1	8.0	6-9	6.5-8.5
2	Manganese, mg/l	23.800/238.0	9.8920/98.9	0.0527	0.0025	0.0055	0.4	0.1
3	Copper, mg/l	0.0379	0.0355	0.0036	0.0009	0.0011	2.0	1.0
4	Zinc, mg/l	0.0454	0.0518	0.0050	0.0022	0.0042	3.0	1.0
5	Lead, mg/l	0.0082	0.0037	0.0015	0.0015	0.0027	0.01	0.03

* - MPC -

6	Cadmium, mg/l	0.0007	0.0002	0.0001	<0.0001	<0.0001	0.003	0.001
7	Nickel, mg/l	0.0201	0.0467	0.0028	0.0008	0.0010	0.07	0.1
8	Cobalt, mg/l	0.0130	0.0097	<0.0001	0.0007	0.0005		0.1
		November, 2025						
1	Manganese, mg/l	60.57/605.7	0.6347/6.4	0.0169	0.0376		0.4	0.1
2	Copper, mg/l	0.0078	0.0041	0.0035	0.0010		2.0	1.0
3	Zinc, mg/l	0.0336	0.0245	0.0025	0.0010		3.0	1.0
4	Lead, mg/l	0.0015	0.0039	0.0011	0.0007		0.01	0.03
5	Cadmium, mg/l	0.0002	0.0002	<0.0001	<0.0001		0.003	0.001
6	Cobalt, mg/l	0.0018	0.0020	0.0027	0.0016			0.1
7	Nickel, mg/l	0.0016	0.0031	0.0042	0.0009		0.07	0.1

Maximum permissible concentration according to the Technical Regulations for Drinking Water (Resolution of the Government of Georgia No. 58 of January 15, 2014, Tbilisi) [10]

** - MPC - Maximum permissible concentration in accordance with the Technical Regulations for Surface Water (Resolution of the Government of Georgia No. 425, December 31, 2013, Tbilisi) [9]

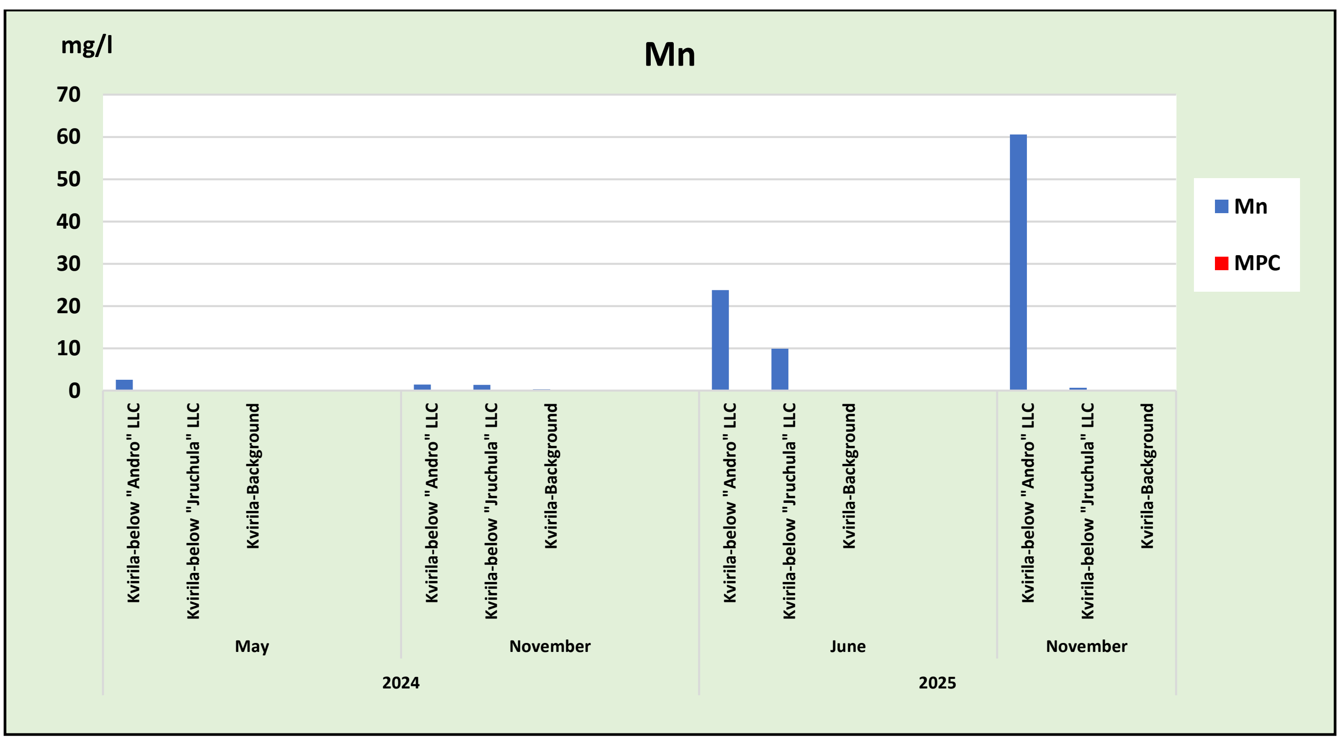


Figure 1. Manganese content in the waters of the Kvirila River - 2024, 2025

As shown in Table 1, similar to the observations made in 2024, the pH values measured downstream of Andro LLC and Jruchula LLC in May 2025 indicated slightly alkaline conditions, ranging from 7.9 to 8.1.

A particularly alarming situation was observed in June 2025 with respect to manganese concentrations in the Kvirila River. Downstream of Andro LLC, the manganese concentration reached 23.800 mg/L, corresponding to 238.0 times the maximum permissible concentration (MPC). Downstream of Jruchula LLC, the manganese concentration was 9.8920 mg/L, equivalent to 98.9 times the MPC (Figure 1).

The manganese concentrations in both spring water samples remained within the permissible limits.

None of the analyzed heavy metals exceeded their respective maximum permissible concentrations.

In November 2025, the manganese concentration downstream of Andro LLC was particularly high, reaching 60.57 mg/L, equivalent to 605.7 times the MPC. Downstream of Jruchula LLC, the concentration was 0.6347 mg/L, corresponding to 6.3 times the MPC. The background concentration of manganese in the Kvirila River was 0.0169 mg/L, which did not exceed the maximum permissible concentration. The concentrations of all analyzed heavy metals also remained below their respective MPC values.

In May 2024, the manganese content in both the suspended solids and bottom sediments of the Kvirila River was high, with particularly elevated concentrations observed downstream of Andro LLC compared with Jruchula LLC. The manganese concentration in the bottom sediments was higher than that in the suspended solids, reaching 68.5 g/kg and 58.3 g/kg, respectively. In contrast, downstream of Jruchula LLC, the manganese concentration was 66.7 g/kg in the bottom sediments and 23.6 g/kg in the suspended solids.

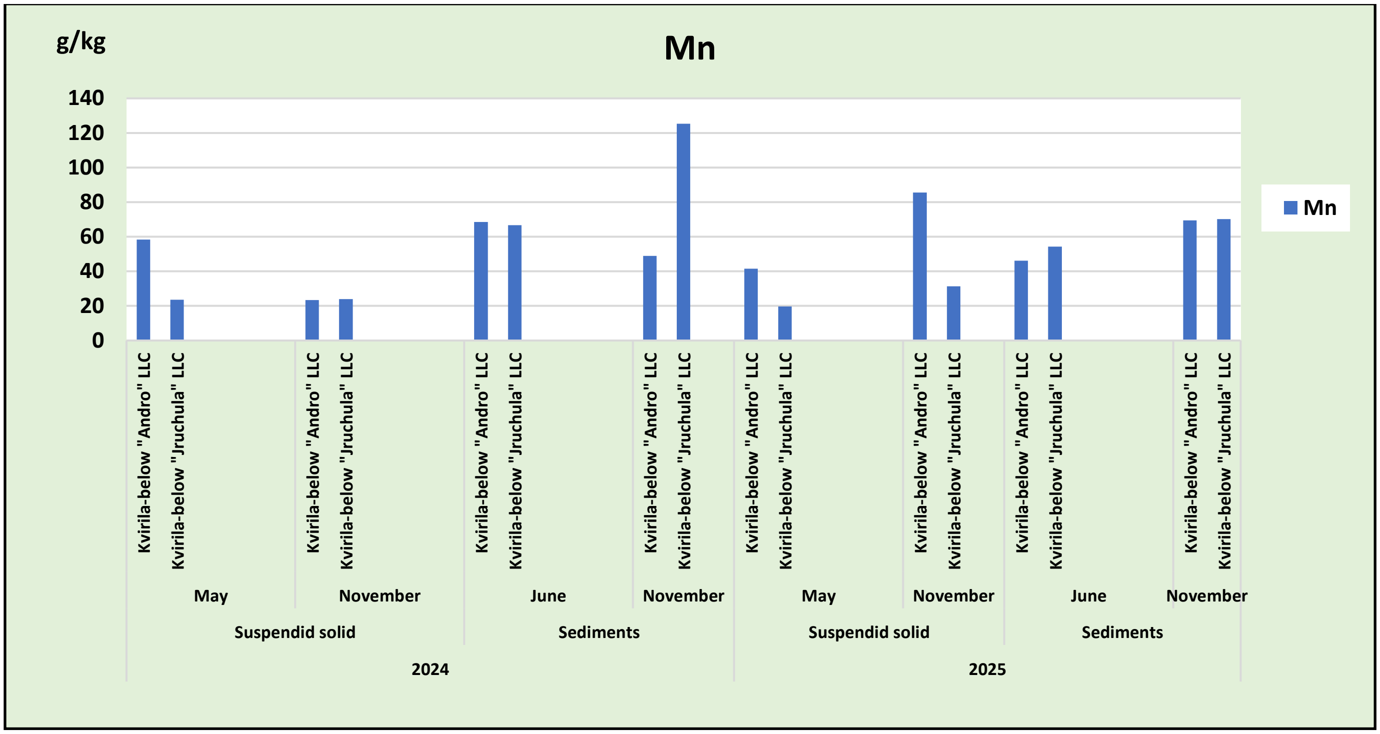
Table 2 presents the manganese concentrations in the suspended solids and bottom sediments of the Kvirila River collected in November 2024. As shown, the manganese concentration in the bottom sediments downstream of Jruchula LLC was particularly high, reaching 125.3 g/kg, whereas downstream of Andro LLC it was considerably lower (48.87 g/kg). Similarly, the manganese concentrations in the suspended solids were 23.37 g/kg and 23.95 g/kg, respectively, indicating manganese contamination of the Kvirila River.

Table 2. Mn content in suspended solids and sediments of the Kvirila River - 2024, 2025

N	Sampling location	Coordinates	Analysis result	
	Suspended solids	**2024**	**g/kg**	
			May	**November**
1	Kvirila-below "Andro" LLC	X-363027 Y-4686103	58.3	23.37
2	Kvirila-below "Jruchula" LLC	X-363791 Y-4686878	23.6	23.95
	Sediments			
1	Kvirila-below "Andro" LLC	X-363027 Y-4686103	68.5	48.87
2	Kvirila-below "Jruchula" LLC	X-363791 Y-4686878	66.7	125.3
	Suspended solids	**2025**	**June**	**November**
1	Kvirila-below "Andro" LLC	X-363027 Y-4686103	41.5	85.5
2	Kvirila-below "Jruchula" LLC	X-363791 Y-4686878	19.7	31.3

	Sediments			
1	Kvirila-below "Andro" LLC	X-363027 Y-4686103	46.1	69.40
2	Kvirila-below "Jruchula" LLC	X-363791 Y-4686878	54.3	70.14

Figure 2. Manganese content in suspended solids and sediments of the Kvirila River - 2024, 2025



In June 2025, the manganese concentrations in the suspended solids of the Kvirila River were higher downstream of Andro LLC than downstream of Jruchula LLC, reaching 41.5 g/kg and 19.7 g/kg, respectively. In contrast, the manganese concentrations in the bottom sediments exceeded those measured in the suspended solids, reaching 54.3 g/kg downstream of Jruchula LLC and 46.1 g/kg downstream of Andro LLC.

Table 2 presents the manganese concentrations in the suspended solids and bottom sediments of the Kvirila River collected in November 2025. The results indicate that the manganese concentration in the bottom sediments downstream of Jruchula LLC was particularly high, reaching 70.1 g/kg, whereas the concentration downstream of Andro LLC was slightly lower at 69.4 g/kg. In contrast, the manganese concentration in the suspended solids was considerably higher downstream of Andro LLC, reaching 85.5 g/kg, while downstream of Jruchula LLC it was substantially lower, measuring 31.3 g/kg.

5. DISCUSSION

Based on the investigations conducted in Chiatura Municipality during 2024–2025, the concentrations of manganese and selected heavy metals were determined in the waters of the Kvirila River, as well as in suspended solids and bottom sediments. The results demonstrated elevated manganese concentrations in the Kvirila River downstream of both manganese-processing enterprises. In these locations, the hazard quotient for surface water (HQ_{SW} > 1) indicates that the river water is potentially at risk. Elevated manganese concentrations were also observed in both suspended solids and bottom sediments, where the results are expressed in g/kg.

With respect to the analyzed heavy metals (Cu, Zn, Pb, Cd, Ni, and Co), all measured concentrations remained below the corresponding maximum permissible concentrations (MPCs). However, in nearly all cases, their concentrations in water samples collected downstream of the industrial facilities were higher than those measured at the background sampling site.

Similar investigations were conducted by our research group during 2022–2025 in the Tskhenistskali and Lukhun rivers of Ambrolauri Municipality using the same analytical methods for determining heavy metals and arsenic and for environmental risk assessment. The results obtained are consistent with our previous findings and are in full agreement with the long-term monitoring data of the National Environmental Agency. Furthermore, the environmental risks associated with various pollutants were evaluated using the methodology developed by the Water Research Institute of the Slovak Republic, which has been successfully applied in our previous studies (Shavliashvili et al., 2025; Tabatadze et al., 2025; Shavliashvili et al., 2025).

It should also be emphasized that intensive manganese extraction is currently carried out within Chiatura Municipality using both underground and open-pit mining methods. In the vicinity of the mining enterprises, the Kvirila River exhibits a characteristic black coloration resulting from the discharge of industrial wastewater generated during the ore-washing process. This wastewater contains large quantities of suspended solids, bottom sediments, heavy metals, and manganese compounds, which are discharged into the Kvirila River without treatment, thereby contributing to significant environmental pollution. The findings of this study have important implications for environmental governance and sustainable water resource management in mining regions. Continuous monitoring of manganese contamination should support evidence-based environmental policies, strengthen regulatory oversight of mining wastewater discharge, and contribute to sustainable resource management strategies in Chiatura Municipality. The results may also assist environmental authorities and policy makers in developing effective pollution mitigation measures that protect both aquatic ecosystems and public health.

6. CONCLUSION

- In 2024, the pH of the Kvirila River ranged from 7.7 to 8.2, while the pH of the spring waters ranged from 7.8 to 8.3. In 2025, the pH of the Kvirila River varied between 7.9 and 8.1, whereas the pH of the spring waters ranged from 8.0 to 8.1. In both years, the waters exhibited a slight shift toward alkaline conditions.

- During 2024–2025, the manganese concentrations measured downstream of the mining enterprises exceeded the maximum permissible concentration (MPC) in almost all cases. This is attributed to the discharge of wastewater generated during the washing of extracted manganese ore into the Kvirila River.

- The calculated manganese hazard quotient for the Kvirila River (HQ_{SW} > 1) indicates that the river water is potentially at risk.

- The total manganese concentrations in the suspended solids and bottom sediments of the Kvirila River were considerably higher than the corresponding background values.

- The manganese concentrations in the spring waters remained below the maximum permissible concentration (MPC). The calculated hazard quotient (HQ_{DW} < 1) indicates that these waters do not pose a potential environmental or human health risk.

- Among the analyzed heavy metals (Cu, Zn, Pb, Cd, Ni, and Co), none exceeded the corresponding maximum permissible concentrations in the natural water samples.

7. DECLARATIONS

Author Contributions

L. Shavliashvili: Conceptualization, methodology, investigation, formal analysis, supervision, writing—original draft, and project administration.

E. Shubladze: Investigation, laboratory analyses, data curation, validation, and writing—review and editing.

G. Kuchava: Methodology, field sampling, laboratory investigation, data interpretation, and visualization.

G. Gavardashvili: Scientific supervision, methodology, validation, interpretation of results, and critical revision of the manuscript.

Z. Rikadze: Environmental data collection, validation, resources, and manuscript review.

All authors have read and approved the final version of the manuscript.

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Data Availability Statement

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Ethical Approval

This study involved environmental monitoring and laboratory analysis of water, suspended solids, and sediment samples. No experiments involving humans or animals were conducted; therefore, ethical approval was not required.

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Declaration of AI Use

The authors declare that no generative artificial intelligence (AI) tools were used in the design of the study, data collection, laboratory analyses, interpretation of results, or preparation of the scientific content of this manuscript. AI-assisted tools, if used, were limited to language editing and grammar improvement and did not contribute to the scientific conclusions of the study.

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