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Risk Assessment of Manganese and Heavy Metal Contamination in Surface and Spring Waters of Chiatura Municipality, Georgia: An Integrated Environmental Monitoring Study (2024–2026)

Gürcistan'ın Çiatura Belediyesi'nde Yüzey ve Kaynak Sularındaki Manganez ve Ağır Metal Kirliliğinin Risk Değerlendirmesi: Bütünleşik Bir Çevresel İzleme Çalışması (2024–2026)

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Abstract
Chiatura Municipality, located in the Imereti region of Georgia, represents one of the country's most environmentally vulnerable mining areas due to more than a century of intensive manganese extraction and ore-processing activities. This study evaluates the contamination risks associated with manganese and selected heavy metals (Cu, Zn, Pb, Cd, Ni, and Co) in the Kvirila River and adjacent spring waters during the period 2024–2026. Water, suspended solids, and bottom sediment samples were collected from both background and mining-affected locations and analyzed using modern analytical methods that comply with European environmental monitoring standards. The concentrations of total manganese and heavy metals were determined, and

Özet
Gürcistan'ın İmereti bölgesinde yer alan Çiatura Belediyesi, yüz yılı aşkın süredir devam eden yoğun manganez madenciliği ve cevher işleme faaliyetleri nedeniyle ülkenin çevresel açıdan en hassas bölgelerinden biridir. Bu çalışma, 2024–2026 yılları arasında Kvirila Nehri ve çevresindeki kaynak sularında manganez ile seçilmiş ağır metallerin (Cu, Zn, Pb, Cd, Ni ve Co) neden olduğu kirlilik risklerini değerlendirmektedir. Arka plan ve madencilik faaliyetlerinden etkilenen bölgelerden su, askıda katı madde ve taban çökeli örnekleri alınmış; analizler Avrupa çevresel izleme standartlarına uygun modern laboratuvar yöntemleri kullanılarak gerçekleştirilmiştir. Toplam manganez ve ağır metal konsantrasyonları belirlenmiş, elde edilen

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contamination levels were assessed through comparison with maximum permissible concentrations and hazard quotient (HQ) indices. The results indicate that manganese is the principal contaminant affecting the aquatic environment. Although the concentrations of Cu, Zn, Pb, Cd, Ni, and Co remained below their respective regulatory limits, manganese concentrations in the Kvirila River exceeded acceptable risk thresholds (HQsw > 1), indicating potential environmental and ecological risks. In contrast, manganese levels in spring waters remained below the hazard threshold (HQdw < 1), suggesting no significant health risk for groundwater resources. Elevated manganese concentrations were also detected in river suspended solids and bottom sediments, confirming long-term accumulation associated with mining activities. The findings provide valuable scientific evidence for environmental monitoring and sustainable water resource management in mining-affected regions.

Keywords: Chiatura Municipality; Kvirila River; manganese; heavy metals; surface water; spring water; environmental pollution; hazard quotient; mining activities; environmental risk assessment.

değerler maksimum izin verilebilir konsantrasyonlar ile tehlike katsayısı (HQ) esas alınarak değerlendirilmiştir. Bulgular, çalışma alanındaki temel kirleticinin manganez olduğunu göstermektedir. Cu, Zn, Pb, Cd, Ni ve Co konsantrasyonları yasal sınırların altında kalırken, Kvirila Nehri'nde manganez için hesaplanan tehlike katsayısı (HQsw > 1) çevresel risk bulunduğunu ortaya koymuştur. Buna karşılık kaynak sularında manganez için hesaplanan HQdw değeri 1'in altında bulunmuş ve önemli bir sağlık riski tespit edilmemiştir. Ayrıca nehirdeki askıda katı maddeler ve taban çökellerinde yüksek manganez birikimi belirlenmiş olup bu durum madencilik faaliyetlerine bağlı uzun dönemli kirlenmeyi doğrulamaktadır. Çalışma, madencilik bölgelerinde sürdürülebilir su yönetimi ve çevresel izleme açısından önemli bilimsel veriler sunmaktadır.

Anahtar Kelimeler: Çiatura Belediyesi; Kvirila Nehri; manganez; ağır metaller; yüzey suları; kaynak suları; çevre kirliliği; tehlike katsayısı; madencilik faaliyetleri; çevresel risk değerlendirmesi.

1. Introduction

Climate change, rapid industrialization, population growth, and intensive exploitation of natural resources have substantially increased environmental pressures worldwide, resulting in accelerated ecosystem degradation and deterioration of water quality. Mining activities, in particular, represent one of the most significant anthropogenic sources of environmental contamination due to the continuous release of suspended solids, heavy metals, and other toxic substances into terrestrial and aquatic ecosystems. The environmental consequences of mining extend beyond the immediate extraction sites, affecting river systems, groundwater resources, soil quality, biodiversity, and ultimately human health (UNEP, 2019; WHO, 2022).

Georgia is considered one of the environmentally sensitive countries in the South Caucasus because of its complex topography, high climatic diversity, and extensive river network. The country encompasses nearly all climatic zones within a relatively small territory, making its ecosystems particularly vulnerable to climate change and anthropogenic disturbances. Recent climatic trends have intensified the frequency and severity of natural hazards, including floods, landslides, mudflows, erosion, and extreme precipitation events, thereby increasing the vulnerability of water resources and environmental infrastructure (MEPA, 2023). These challenges have become especially evident in regions where intensive industrial activities coincide with fragile natural environments.

Among these regions, Chiatura Municipality, located in western Georgia, represents one of the country's most environmentally vulnerable mining districts. Since the discovery of manganese deposits in the nineteenth century, the municipality has developed into one of the world's major manganese extraction and processing centers. Although mining has contributed substantially to regional economic development and employment, decades of intensive exploitation have generated considerable environmental challenges, including landscape degradation, deforestation, habitat fragmentation, soil erosion, river pollution, and the accumulation of mining waste (Shavliashvili et al., 2023). These environmental pressures have been further aggravated by climate-induced increases in heavy rainfall and surface runoff, which facilitate the transport of mining residues into surrounding ecosystems.

The Kvirila River, the principal river flowing through Chiatura Municipality, plays a critical ecological and socio-economic role in the region. However, it is also one of the aquatic ecosystems most directly affected by mining activities. During ore washing and processing, industrial wastewater containing high concentrations of suspended particles, manganese compounds, and trace metals is generated. In many cases, these effluents enter the river system with insufficient treatment, contributing to the deterioration of water quality. Additional contamination originates from large tailing deposits and agglomerate waste storage sites located adjacent to the river. Atmospheric precipitation and surface runoff continuously mobilize manganese-rich materials from these waste deposits, introducing additional pollutant loads into the aquatic environment and increasing sediment contamination.

Unlike many trace metals, manganese is an essential micronutrient required for numerous physiological processes in humans, animals, and plants. It plays an important role in enzyme activation, carbohydrate and lipid metabolism, bone formation, photosynthesis, and antioxidant defense mechanisms. Nevertheless, excessive environmental exposure to manganese represents a significant public health concern. Chronic exposure may lead to neurological disorders, respiratory diseases, dermatological complications, and other toxicological effects due to its cumulative behavior within biological systems. Consequently, continuous environmental monitoring of manganese concentrations is essential for protecting both ecosystem integrity and human health (WHO, 2022).

Heavy metals such as copper (Cu), zinc (Zn), lead (Pb), cadmium (Cd), nickel (Ni), and cobalt (Co) are also recognized as priority environmental pollutants because of their persistence, toxicity, bioaccumulation potential, and adverse ecological impacts. Even when present below regulatory thresholds, prolonged exposure may contribute to sediment contamination and ecological imbalance. Therefore, integrated assessments of dissolved metals, suspended solids, and bottom sediments provide a more comprehensive understanding of pollution dynamics than water analysis alone.

Against this background, the present study aims to evaluate the contamination status and environmental risks associated with manganese and selected heavy metals in the Kvirila River and adjacent spring waters of Chiatura Municipality during the period 2024–2026. Water, suspended solids, and bottom sediment samples collected from background and mining-affected sites were analyzed using analytical methods consistent with European environmental standards. Risk assessment was performed through comparison with maximum permissible concentrations (MPCs) and hazard quotient (HQ) indices. The findings contribute to a better understanding of mining-related environmental pollution in Georgia and provide scientific evidence to support sustainable water resource management, environmental monitoring, and pollution mitigation strategies in mining-affected regions.

2. Literature Review

Mining activities have long been recognized as one of the principal anthropogenic sources of heavy metal contamination in freshwater ecosystems. The extraction and processing of mineral resources frequently generate large quantities of mine wastewater, suspended solids, and waste rock that introduce trace metals into rivers, lakes, groundwater, and surrounding soils. These pollutants often persist in aquatic environments because of their non-biodegradable nature, posing long-term ecological and human health risks through bioaccumulation and sediment enrichment. Recent international studies emphasize that environmental assessments of mining regions should integrate water chemistry, suspended particulate matter, and bottom sediments to accurately characterize contamination pathways and ecological risks.

Among mining-related contaminants, manganese (Mn) has attracted increasing scientific attention because it represents both an essential micronutrient and a potentially hazardous environmental pollutant when present at elevated concentrations. While manganese is indispensable for metabolic processes in plants, animals, and humans, excessive environmental exposure has been associated with neurological disorders, ecological toxicity, and degradation of freshwater ecosystems. Contemporary reviews indicate that manganese released from mining operations is frequently transported through atmospheric deposition, surface runoff, industrial effluents, and weathering of mine wastes, leading to widespread contamination of rivers and sediments. Sustainable management therefore requires continuous monitoring combined with comprehensive environmental risk assessment and remediation planning.

Previous investigations conducted in mining regions throughout the world have consistently demonstrated elevated concentrations of manganese and associated heavy metals downstream of mining operations. Studies in China reported significant enrichment of manganese, lead, zinc, and copper in river sediments affected by manganese mining, with ecological risk indices indicating potential threats to aquatic ecosystems despite variations in dissolved metal concentrations. Similar findings have been reported from mining-impacted river basins in South America, Africa, and Asia, where heavy metals accumulate preferentially within suspended solids and bottom sediments rather than remaining dissolved in the water column. These observations underline the necessity of sediment monitoring alongside conventional water-quality assessments.

Within Georgia, Chiatura Municipality has been the subject of several environmental investigations because it contains one of the world's largest and historically most productive manganese mining districts. One of the earliest comprehensive international studies examining water quality in the region was conducted by Caruso et al., who investigated the effects of manganese mining on the Kvirila River, tributaries, industrial wastewater, and drinking-water sources. Their research demonstrated substantially elevated concentrations of manganese and iron downstream of mining and ore-processing facilities, while river sediments contained considerable accumulations of trace metals. The authors concluded that particulate transport represented the dominant pathway of manganese migration within the Kvirila River system and emphasized the need for continuous environmental monitoring.

National studies have similarly documented the environmental consequences of intensive manganese extraction in Chiatura. Reports prepared by the Grigol Tsulukidze Mining Institute and environmental management organizations identified untreated industrial wastewater, mine tailings, and agglomerate disposal sites as major pollution sources affecting the Kvirila River. Additional investigations have emphasized that increased precipitation and erosion accelerate the transport of manganese-rich materials into surrounding aquatic ecosystems, thereby increasing contamination of river sediments and downstream environments. These studies also highlight the cumulative impacts of mining on landscape degradation, biodiversity loss, and deterioration of water quality.

Environmental monitoring frameworks increasingly recommend the use of risk-based assessment methods rather than relying exclusively on comparisons with maximum permissible concentrations (MPCs). Hazard Quotient (HQ) models have become widely accepted tools for evaluating the potential health and ecological risks associated with exposure to heavy metals in drinking water and surface waters. International risk assessment methodologies integrate contaminant concentrations with toxicological reference values to determine whether environmental exposure exceeds acceptable safety thresholds. Such approaches provide more comprehensive information for environmental management and public health protection than concentration-based assessments alone.

Recent studies conducted by Shavliashvili and colleagues have expanded knowledge regarding heavy metal contamination in different regions of Georgia through investigations of arsenic-contaminated soils, hydrochemical characteristics of natural waters, and environmental pollution associated with mining waste. Their findings demonstrate the effectiveness of integrated chemical analyses, statistical evaluation, and environmental monitoring for identifying contamination sources and assessing ecological risks. These methodological approaches provide an important scientific basis for evaluating manganese contamination in the Chiatura mining district and support the application of internationally recognized environmental assessment techniques.

Despite the growing body of literature concerning mining-related pollution, important research gaps remain regarding the long-term environmental risks associated with manganese contamination in Chiatura Municipality. Previous investigations have primarily focused on water quality or sediment contamination independently, while comparatively few studies have simultaneously examined surface waters, spring waters, suspended solids, and bottom sediments using integrated environmental risk assessment approaches. Furthermore, limited information exists regarding recent contamination trends following intensified mining activities during the past decade.

The present study addresses these research gaps by conducting a comprehensive environmental assessment of manganese and selected heavy metals (Cu, Zn, Pb, Cd, Ni, and Co) in the Kvirila River and adjacent spring waters during 2024–2026. By combining chemical analyses of water, suspended solids, and bottom sediments with hazard quotient assessment, this research contributes updated scientific evidence regarding mining-related contamination and provides practical information for sustainable environmental management and water resource protection in Chiatura Municipality.

3. Materials and Methods

3.1. Study Area

The present study was conducted in Chiatura Municipality, located in the Imereti Region of western Georgia, one of the country's most important manganese mining districts. Industrial extraction and beneficiation of manganese ore have been carried out continuously in the region since the late nineteenth century, making Chiatura one of the oldest active manganese-producing areas worldwide. The Kvirila River, the principal river crossing the municipality, plays an essential ecological and socio-economic role, supplying water for industrial ore washing while simultaneously receiving wastewater generated during mining and mineral processing activities. Consequently, the river is exposed to elevated inputs of suspended solids, manganese compounds, and trace metals originating from mining operations, waste disposal sites, and ore-processing facilities (World Resources Institute, 2003; LEPL Grigol Tsulukidze Mining Institute et al., 2010).

3.2. Sampling Strategy

Field investigations were carried out during 2024–2026 to evaluate the environmental impact of manganese mining on surface and groundwater resources. Samples were collected from locations representing both background (reference) conditions and sites situated downstream of manganese processing facilities, thereby allowing direct assessment of anthropogenic impacts on water quality.

The monitoring program included four environmental matrices:

- surface water samples from the Kvirila River;
- spring (drinking) water samples;
- suspended solids collected from river water;
- bottom sediment samples from the Kvirila River.

The inclusion of suspended solids and bottom sediments enabled the assessment of long-term accumulation and transport of contaminants in addition to dissolved concentrations in surface waters, providing a comprehensive evaluation of mining-related pollution.

3.3. Physicochemical and Chemical Analysis

The physicochemical characteristics of all water samples were determined immediately after sampling. Measurements included pH together with the concentrations of total manganese (Mn) and selected heavy metals, including copper (Cu), zinc (Zn), lead (Pb), cadmium (Cd), nickel (Ni), and cobalt (Co).

Laboratory analyses were performed according to internationally recognized analytical procedures using instrumentation that complies with European environmental monitoring standards (Fomin & Fomin, 2001).

The analytical equipment included:

- Inductively Coupled Plasma Optical Emission Spectrometry (ICP–OES) following EPA Method 200.8 for determination of manganese and heavy metal concentrations;
- Hanna HI98129 Combo pH/EC/TDS/Temperature Meter for in situ physicochemical measurements;
- Milwaukee MI150 laboratory pH meter for verification of pH measurements.

Quality assurance and quality control (QA/QC) procedures included instrument calibration using certified reference standards, duplicate analyses, reagent blanks, and routine verification of analytical precision throughout the monitoring period.

3.4. Environmental Risk Assessment

Potential environmental risks associated with manganese contamination were evaluated using the Hazard Quotient (HQ) approach, which is widely applied in environmental risk assessment for surface waters and drinking water (Water Research Institute of the Slovak Republic, 2019).

The hazard quotient was calculated using Equation (1):

$$HQ = \frac{MC}{EQS}$$

where:

- HQ = Hazard Quotient;
- MC = measured manganese concentration (mg L^{-1});
- EQS = Environmental Quality Standard for the corresponding water category.

An HQ value greater than 1 ($HQ > 1$) indicates potential environmental risk and suggests that manganese concentrations exceed acceptable environmental quality standards, whereas $HQ < 1$ indicates negligible environmental risk.

Environmental Quality Standards (EQS) were adopted according to Georgian national legislation:

- Surface waters: 0.10 mg L^{-1}, in accordance with Government of Georgia Resolution No. 425 on the Technical Regulations for the Protection of Surface Waters from Pollution (Government of Georgia, 2013);
- Drinking waters: 0.40 mg L^{-1}, in accordance with Government of Georgia Resolution No. 58 on the Technical Regulations for Drinking Water Quality (Government of Georgia, 2014).

3.5. Data Evaluation

Measured concentrations of manganese and heavy metals were compared with background values and national maximum permissible concentrations (MPCs). In addition to evaluating compliance with regulatory standards, spatial differences between upstream reference locations and downstream mining-affected sites were examined to identify contamination patterns associated with manganese extraction and ore-processing activities.

The combined evaluation of surface waters, spring waters, suspended solids, bottom sediments, and hazard quotient indices provided an integrated assessment of mining-related environmental contamination and ecological risk within the Kvirila River basin, consistent with internationally accepted environmental monitoring methodologies (Water Research Institute of the Slovak Republic, 2019; World Resources Institute, 2003).

3. Results

Table 1 shows the heavy metal concentrations in the waters of the Kvirila rivers and spring water in 2024 and 2025. The numerator shows the manganese concentration, and the denominator shows the maximum permissible concentration (MPC).

As can be seen from Table 1, in May 2024, below Kvirila-LLC "Andro" and Kvirila-LLC "Jruchula", a deviation of pH in the alkaline direction is observed and amounts to 8.1-8.2 compared to the Kvirila background (7.7). The manganese concentration is equal to 2.5649 mg/l, which is 25.6 MPC; while below Kvirila-LLC "Jruchula" - 0.1136 mg/l, which is 1.1 MPC. This is due to the fact that below Kvirila-LLC "Andro" the Kvirila River is polluted by the discharge of wastewater into the Kvirila River as a result of washing the mined ore; And below Kvirila-LLC "Jruchula" - the low concentration indicates that the enterprise may not have been operating at full capacity during that period (Fig. 1).

The manganese content in the water of both springs is within the normal range.

Of the heavy metals determined, except for manganese, no metal was found in quantities exceeding the MPC (Table 1, Fig. 1).

The manganese content in the water of the Kvirila River in November below the Andros LLC is 13.9 mg/L, and below the Jruchula LLC - 13.7 mg/L. It is noteworthy that even in the background value of the Kvirila River, the manganese content is high and amounts to 0.2572 mg/L (2.6 mg/L). The content of heavy metals is less than the MPC in all cases.

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	pring water 1	Spring water - 2	PC*	PC**
		May, 2024						
	pH	8.1	8.2	7.7	.2	7.8	-9	.5-8.5
	Manganese, mg/l	2.5649/25.6	0.1136/1.1	0.0150	.0154	0.0030	.4	.1
	Copper, mg/l	0.0134	0.0024	0.0040	.0028	0.0008	.0	.0
	Zinc, mg/l	0.0054	0.0035	0.0012	.0031	0.0009	.0	.0
	Lead, mg/l	0.0023	0.0011	0.0008	.0021	0.0015	.01	.03
	Cadmium, mg/l	0.0002	0.0001	0.0001	0.0001	<0.0001	.003	.001
	Nickel, mg/l	0.0005	0.0023	0.0007	.0010	0.0005	.07	.1
	Cobalt, mg/l	0.0004	0.0007	0.0003	.0012	0.0009		.1
		November, 2024						
	Manganese, mg/l	1.3958/13.9	1.3742/13.7	0.2572/2.6	.0050		.4	.1
	Copper, mg/l	0.0032	0.0038	0.0040	.0010		.0	.0
	Zinc, mg/l	0.0522	0.0456	0.0013	.0008		.0	.0
	Lead, mg/l	0.0012	0.0024	0.0009	.0011		.01	.03
	Cadmium, mg/l	0.0003	0.0004	< 0.0001	0.0001		.003	.001
	Cobalt, mg/l	0.0011	0.0007	0.0005	.0003			.1
	Nickel, mg/l	0.0023	0.0033	0.0015	.0004		.07	.1
		June, 2025						
	pH	7.9	8.0	8.1	.1	8.0	-9	.5-8.5
	Manganese, mg/l	23.800/238.0	9.8920/98.9	0.0527	.0025	0.0055	.4	.1

	Copper, mg/l	0.0379	0.0355	0.0036	.0009	0.0011	.0	.0
	Zinc, mg/l	0.0454	0.0518	0.0050	.0022	0.0042	.0	.0
	Lead, mg/l	0.0082	0.0037	0.0015	.0015	0.0027	.01	.03
	Cadmium, mg/l	0.0007	0.0002	0.0001	0.0001	< 0.0001	.003	.001
	Nickel, mg/l	0.0201	0.0467	0.0028	.0008	0.0010	.07	.1
	Cobalt, mg/l	0.0130	0.0097	< 0.0001	.0007	0.0005		.1
		November, 2025						
	Manganese, mg/l	60.57/605.7	0.6347/6.4	0.0169	.0376		.4	.1
	Copper, mg/l	0.0078	0.0041	0.0035	.0010		.0	.0
	Zinc, mg/l	0.0336	0.0245	0.0025	.0010		.0	.0
	Lead, mg/l	0.0015	0.0039	0.0011	.0007		.01	.03
	Cadmium, mg/l	0.0002	0.0002	< 0.0001	0.0001		.003	.001
	Cobalt, mg/l	0.0018	0.0020	0.0027	.0016			.1
	Nickel, mg/l	0.0016	0.0031	0.0042	.0009		.07	.1

* - MPC - 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]

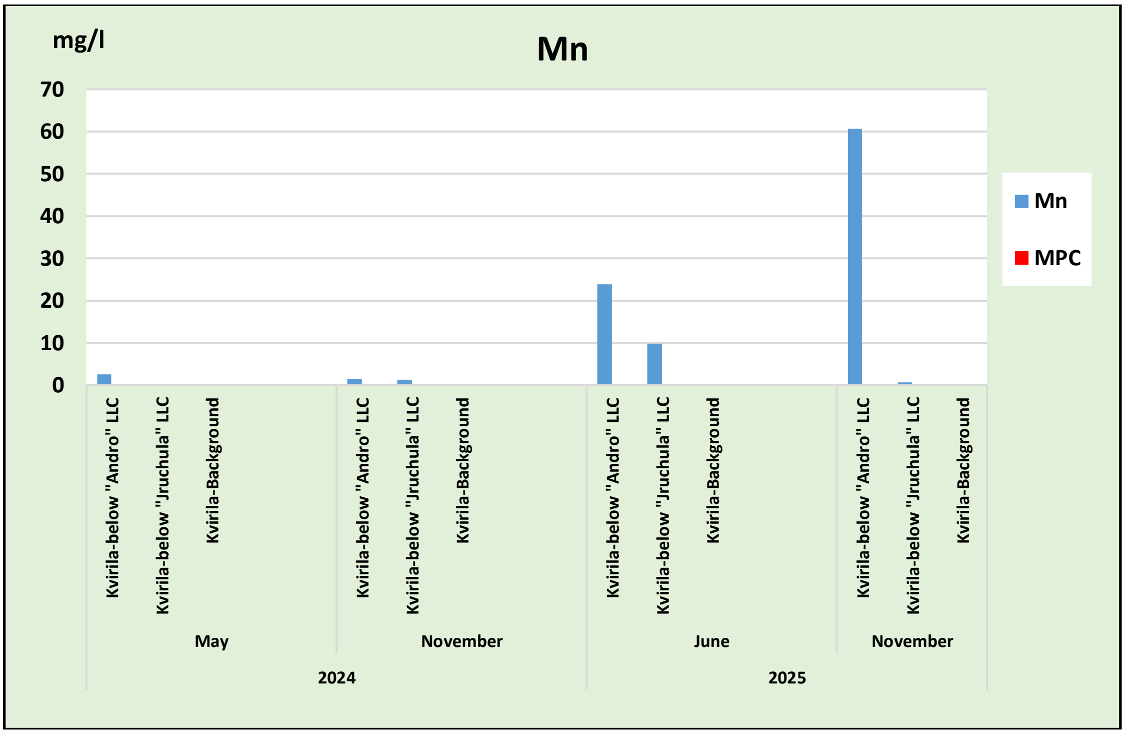

Figure 1. Manganese content in the waters of the Kvirila River - 2024, 2025

As can be seen from Table 1, in May 2025, similarly to 2024, below LLC “Andro” and Kvirila-LLC “Jruchula”, a deviation of pH in the alkaline direction is observed and amounts to 7.9 - 8.1.

An alarming situation is observed in June 2025 in terms of manganese content in the river Kvirila below LLC “Andro”, where the manganese concentration is equal to 23.800, which is equal to 238.0 MPC, and in Kvirila-„Jruchula” it is -9.8920 mg/l, which is 98.9 MPC (Fig. 1).

The manganese content in the water of both springs is within the normal range.

Of the heavy metals determined, none of the metals were found to be in excess of the MPC.

The manganese content in the water of the Kvirila River in November 2025 below the LLC "Andros" is particularly high and amounts to 60.57 mg/l (605.7 MPC), and below the LLC "Jruchula" -0.6347 mg/l (6.3 MPC); the manganese content at the background point of the Kvirila River is 0.0169 mg/l and does not exceed the MLD; the content of heavy metals here is also less than the MPC in all cases.

In May 2024, the Mn content in the suspended solids and bottom sediments of the Kvirila River is high, especially its content is especially high with "Andro" LLC compared to "Jruchula" LLC. At the same time, the Mn content in the bottom sediments is higher than in the suspended solids and is 68.5 and 58.3 g/kg, respectively. While the manganese content in the bottom sediments at "Jruchula" is 66.7 and in the suspended solids - 23.6 g/kg.

In November, Table 2 shows the Mn content in the suspended solids and sediments of the Kvirila River (November, 2024). As the analysis results show, the manganese content in the sediments below the Kvirila-LLC “Jruchula” is particularly high and amounts to 125.3 g/kg, while below the Kvirila-LLC “Andro” - it is much lower (48.87 g/kg). The manganese content in the suspended solids is similarly high and amounts to 23.37 and 23.95 mg/kg, which indicates manganese pollution of the Kvirila River.

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

	Sampling location	**Coordinates**	**Analysis result**	
	Suspended solids	**2024**	**g/kg**	
			May	**November**
	Kvirila-below "Andro" LLC	X-363027 Y-4686103	58.3	23.37
	Kvirila-below "Jruchula" LLC	X-363791 Y-4686878	23.6	23.95
	Sediments			
	Kvirila-below "Andro" LLC	X-363027 Y-4686103	68.5	48.87
	Kvirila-below "Jruchula" LLC	X-363791 Y-4686878	66.7	125.3
	Suspended solids	**2025**	**June**	**November**
	Kvirila-below "Andro" LLC	X-363027 Y-4686103	41.5	85.5
	Kvirila-below "Jruchula" LLC	X-363791 Y-4686878	19.7	31.3
	Sediments			
	Kvirila-below "Andro" LLC	X-363027 Y-4686103	46.1	69.40

	Kvirila-below "Jruchula" LLC	X-363791 Y-4686878	54.3	7 0.14

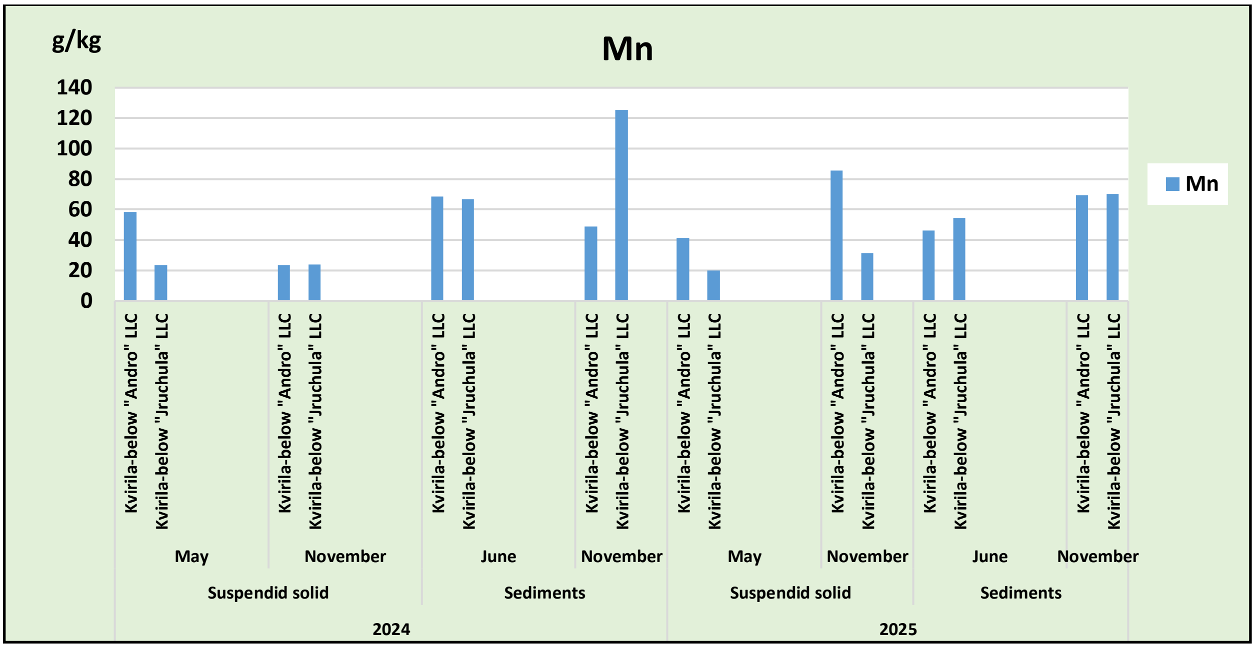

Figure 2. Manganese content in suspended solids and sediments of the Kvirila River - 2024, 2025

In June 2025, the manganese content in the suspended solids and bottom sediments of the Kvirila River is higher below the Andro LLC in the Kvirila River compared to the Jruchula LLC and is 41.5 and 19.7 mg/kg, respectively. Meanwhile, the manganese content in the bottom sediments is higher compared to the suspended solids and is 54.3 below the Jruchula LLC and 46.1 g/kg below the Andro LLC.

Table 2 shows the Mn content in the suspended solids and sediments of the Kvirila River in November (November, 2025). As the analysis results show, the manganese content in the sediments below the Kvirila-LLC “Jruchula” is particularly high and amounts to 70.1 g/kg, while below the Kvirila-LLC “Andro” it is slightly lower (69.4 g/kg). On the contrary, below the LLC “Andro” the manganese content is high and amounts to 85.5 g/kg, in the suspended solids, while below the LLC “Jruchula” it is much lower and amounts to 31.3 g/kg.

5. Discussion

The present study provides a comprehensive assessment of manganese and heavy metal contamination in the Kvirila River and adjacent spring waters of Chiatura Municipality during the 2024–2026 monitoring period. The findings demonstrate that manganese remains the dominant pollutant associated with intensive mining and ore-processing activities in the region, whereas the concentrations of other investigated heavy metals (Cu, Zn, Pb, Cd, Ni, and Co) generally remain below the maximum permissible concentrations (MPCs). These results are consistent with previous investigations indicating that manganese mining primarily contributes to elevated manganese concentrations while simultaneously increasing the transport of suspended solids and trace metals into adjacent aquatic ecosystems (Caruso et al., 2012; World Resources Institute, 2003; Friends of the Earth Europe, 2007).

One of the most important findings of the present investigation is the substantial increase in manganese concentrations downstream of ore-processing enterprises. The calculated hazard quotient for surface waters (HQ_{SW}) consistently exceeded the critical threshold of one, indicating a potential environmental risk associated with prolonged manganese exposure. Although the concentrations of Cu, Zn, Pb, Cd, Ni, and Co remained below regulatory limits established by Georgian legislation (Government of Georgia, 2013; Government of Georgia, 2014), their concentrations downstream of mining facilities were consistently higher than corresponding background values. This observation suggests a measurable anthropogenic influence of mining activities on river water quality despite compliance with current environmental standards. Similar findings have been reported in mining regions worldwide, where trace metal enrichment is frequently observed even when concentrations remain below legally established thresholds (World Resources Institute, 2003; Water Research Institute of the Slovak Republic, 2019).

The elevated manganese concentrations identified in suspended solids and bottom sediments constitute another important finding of this study. Unlike dissolved contaminants, particulate-bound manganese accumulates over extended periods, serving as both a long-term environmental reservoir and a secondary source of contamination during high-flow events, floods, and sediment resuspension. Consequently, sediment analysis provides a more reliable indicator of historical pollution than water chemistry alone. Similar conclusions have been reported in international studies of mining-affected watersheds, where sediment contamination frequently reflects long-term anthropogenic inputs even when dissolved concentrations fluctuate seasonally (Fomin & Fomin, 2001; Water Research Institute of the Slovak Republic, 2019).

The relatively low concentrations of manganese observed in spring waters represent a positive environmental finding. Throughout the monitoring period, manganese concentrations remained below the corresponding maximum permissible concentration, while hazard quotient values for drinking water (HQ_{DW}) remained below one. These results suggest that groundwater resources surrounding the investigated sites currently experience limited influence from mining-derived manganese contamination. Nevertheless, continued hydrogeological monitoring remains essential because prolonged mining activities, changing groundwater flow conditions, and increasing climatic variability may alter contaminant migration pathways in the future (Government of Georgia, 2014; WHO, 2022).

The environmental situation observed in Chiatura Municipality is closely associated with the technological characteristics of manganese extraction and ore processing. Intensive underground and open-pit mining generate substantial quantities of wastewater containing suspended particles, manganese compounds, and trace metals. According to field observations conducted during the present investigation, the Kvirila River exhibited a distinct dark coloration downstream of processing facilities, reflecting the discharge of untreated or insufficiently treated industrial wastewater generated during ore washing. In addition, large waste disposal sites located adjacent to the river continuously release manganese-rich particles through surface runoff and precipitation, thereby increasing both dissolved and particulate contamination. Previous environmental reports prepared for the Chiatura mining district similarly identified untreated wastewater, waste dumps, and tailing deposits as the principal pollution sources affecting the Kvirila River ecosystem (LEPL Grigol Tsulukidze Mining Institute et al., 2010; Liberali, 2018).

Comparison of the present findings with previous investigations conducted by our research group further confirms the reliability of the applied methodology. Earlier studies performed in the Tskhenistskali and Lukhuni river basins during 2022–2025 using identical analytical procedures and environmental risk assessment approaches produced comparable results regarding the behavior of arsenic and heavy metals in mining-affected aquatic environments (Shavliashvili et al., 2025a; Tabatadze et al., 2025; Shavliashvili et al., 2025b). Furthermore, application of the Slovak Water Research Institute hazard assessment methodology has consistently produced robust environmental risk evaluations under Georgian hydrogeological conditions, supporting its suitability for long-term environmental monitoring (Water Research Institute of the Slovak Republic, 2019).

The results obtained also correspond closely with long-term environmental monitoring conducted by the National Environmental Agency of Georgia, indicating that manganese contamination remains the principal environmental concern within the Chiatura mining district. The agreement between independent monitoring programs strengthens confidence in the analytical procedures employed and confirms the persistence of manganese pollution despite ongoing environmental management efforts.

Overall, the findings demonstrate that environmental assessments based solely on maximum permissible concentrations may underestimate mining-related ecological impacts. Although most heavy metals remained within regulatory limits, elevated background enrichment, high sediment accumulation, and hazard quotient analysis reveal continuing anthropogenic pressure on the aquatic ecosystem. Therefore, integrated environmental monitoring combining chemical analysis, sediment assessment, and quantitative risk evaluation provides a more comprehensive understanding of pollution dynamics than conventional water-quality assessment alone (WHO, 2022; Water Research Institute of the Slovak Republic, 2019; World Resources Institute, 2003).

6. Conclusion

The present study evaluated manganese and selected heavy metal contamination in the Kvirila River and adjacent spring waters of Chiatura Municipality during 2024–2026 using integrated environmental monitoring and risk assessment approaches.

The results demonstrated that the pH of both the Kvirila River and spring waters remained within slightly alkaline conditions throughout the monitoring period, varying between 7.7–8.2 in river waters and 7.8–8.3 in spring waters during 2024, and between 7.9–8.1 and 8.0–8.1, respectively, during 2025. These values indicate relatively stable hydrochemical conditions despite intensive mining activities.

Among all investigated contaminants, manganese was identified as the principal environmental pollutant. Surface-water samples collected downstream of manganese processing facilities consistently exhibited manganese concentrations exceeding the maximum permissible concentration, confirming the direct influence of industrial wastewater generated during ore washing. Hazard quotient analysis further demonstrated that HQ_{SW} values exceeded the acceptable safety threshold ($HQ > 1$), indicating potential environmental and ecological risks associated with prolonged manganese exposure.

The investigation also revealed substantial accumulation of manganese within suspended solids and bottom sediments, confirming that river sediments function as long-term repositories of mining-derived contaminants. In contrast, spring waters exhibited manganese concentrations below regulatory limits, and calculated HQ_{DW} values remained below one, indicating no significant health risk associated with groundwater resources during the study period.

Although the concentrations of Cu, Zn, Pb, Cd, Ni, and Co remained below their respective maximum permissible concentrations, elevated concentrations relative to background conditions were observed downstream of mining operations, reflecting measurable anthropogenic influence on river water quality.

Overall, the study demonstrates that intensive manganese mining continues to exert considerable pressure on the aquatic environment of Chiatura Municipality. Continuous environmental monitoring, effective industrial wastewater treatment, improved mine waste management, and regular assessment of sediments and groundwater are essential for reducing environmental risks and ensuring the sustainable management of water resources in this internationally significant mining region.

7. Declarations

Funding

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Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this study.

Ethical Approval

Ethical approval was not required for this study because it did not involve human participants, animal experiments, clinical investigations, or the collection of personal data. The research was based exclusively on environmental sampling and laboratory analysis of surface water, spring water, suspended solids, and bottom sediment samples.

Informed Consent

Not applicable.

Data Availability Statement

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request. Supporting environmental monitoring data are retained by the research team in accordance with the project requirements of the Shota Rustaveli National Science Foundation of Georgia.

Author Contributions

All authors contributed substantially to the conception and design of the study. L. Shavliashvili, E. Shubladze, and G. Kuchava carried out field investigations, laboratory analyses, and data collection. G. Gavardashvili contributed to the research methodology, interpretation of the results, and scientific supervision. Z. Rikadze participated in environmental data evaluation, manuscript revision, and validation of the findings. All authors contributed to the preparation, critical revision, and approval of the final manuscript.

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Declaration of Generative AI and AI-Assisted Technologies

The authors declare that no generative artificial intelligence (AI) or AI-assisted technologies were used in the design of the study, data collection, laboratory analyses, interpretation of results, or preparation of the scientific content of this manuscript.

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Genişletilmiş Özet

Giriş

Madencilik faaliyetleri, dünya genelinde su kaynaklarının ağır metaller ve askıda katı maddelerle kirlenmesine neden olan en önemli antropojenik çevresel baskılardan biridir. Gürcistan'ın İmereti bölgesinde bulunan Çiatura Belediyesi, yaklaşık 150 yıldır sürdürülen yoğun manganez madenciliği nedeniyle ülkenin çevresel açıdan en hassas bölgelerinden biri olarak kabul edilmektedir. Kvirila Nehri, cevher zenginleştirme tesislerinde yıkama suyu olarak kullanılmakta ve arıtılmadan deşarj edilen endüstriyel atık sular nedeniyle sürekli kirlenme baskısı altında bulunmaktadır. Bu çalışma, 2024–2026 yılları arasında Kvirila Nehri ve çevresindeki kaynak sularında manganez ile seçilmiş ağır metallerin çevresel risklerini değerlendirerek madencilik faaliyetlerinin su kalitesi üzerindeki etkilerini ortaya koymayı amaçlamaktadır.

Yöntem

Araştırma kapsamında Kvirila Nehri'nin referans (arka plan) noktalarından ve madencilik faaliyetlerinden etkilenen bölgelerinden yüzey suyu örnekleri alınmıştır. Ayrıca kaynak suları, askıda katı maddeler ve taban çökelleri de analiz edilmiştir. Numunelerde pH ile birlikte toplam manganez (Mn) ve Cu, Zn, Pb, Cd, Ni ve Co konsantrasyonları Avrupa standartlarına uygun laboratuvar yöntemleri kullanılarak belirlenmiştir. Kimyasal analizlerde ICP–OES (EPA Method 200.8) cihazı kullanılmış, çevresel risk değerlendirmesi ise ölçülen manganez konsantrasyonlarının yüzey ve içme suyu kalite standartlarıyla karşılaştırılmasına dayanan Tehlike Katsayısı (Hazard Quotient, HQ) yöntemiyle gerçekleştirilmiştir.

Bulgular

Araştırma sonuçları, Kvirila Nehri'nde madencilik tesislerinin aşağı kesimlerinde manganez konsantrasyonlarının çevresel kalite standartlarını aştığını ve yüzey suları için hesaplanan HQ değerlerinin 1'in üzerinde olduğunu göstermiştir. Buna karşılık Cu, Zn, Pb, Cd, Ni ve Co konsantrasyonları yasal sınırların altında kalmasına rağmen referans noktalara göre artış göstermiştir. Kaynak sularında manganez konsantrasyonları ve HQ değerleri güvenli sınırlar içerisinde bulunmuştur. Askıda katı maddeler ve taban çökellerinde ise yüksek miktarda manganez birikimi tespit edilmiş, bu durum uzun yıllardır devam eden madencilik faaliyetlerinin nehir ekosistemi üzerinde önemli birikim etkisi oluşturduğunu ortaya koymuştur.

Sonuç

Çalışma, Çiatura Belediyesi'nde yürütülen yoğun manganez madenciliğinin özellikle Kvirila Nehri'nin su kalitesi üzerinde belirgin çevresel etkiler oluşturduğunu göstermektedir. Manganez, incelenen kirleticiler arasında en yüksek çevresel riski oluşturan element olarak belirlenmiş, diğer ağır metaller ise yasal sınırlar içinde kalmıştır. Bununla birlikte sedimentlerdeki yüksek manganez birikimi uzun dönemli kirlenmenin sürdüğünü göstermektedir. Bulgular, yalnızca su analizlerinin yeterli olmadığını; yüzey suları, kaynak suları, askıda katı maddeler ve taban çökellerinin birlikte değerlendirilmesi gerektiğini ortaya koymaktadır. Düzenli çevresel izleme, etkin atık su arıtımı ve sürdürülebilir madencilik uygulamaları bölgedeki su kaynaklarının korunması açısından büyük önem taşımaktadır.