

# ENVIRONMENTAL RISK ASSESSMENT OF MANGANESE (Mn) ACCUMULATION IN GEORGIA'S BLACK SEA BASIN RIVERS: A CASE STUDY OF THE KVIRILA RIVER

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## Abstract

*The accumulation of manganese (Mn) in freshwater systems has become a significant environmental and public health concern, especially in areas impacted by intensive mining activities. This study examines the temporal dynamics and regulatory compliance of manganese concentrations in the Kvirila River in Georgia between 2017 and 2023. Analysis of monthly maximum concentration data obtained from Georgia's National Environmental Agency (NEA) reveals widespread and persistent exceedances of the national regulatory threshold of 0.1 mg/L. Almost 80% of the recorded measurements exceeded the permitted limit, with particularly high concentrations observed near the cities of Zestaponi and Chiatura – regions that have been heavily impacted by manganese mining in the past. Seasonal patterns were evident, with peak concentrations typically occurring during the summer and autumn months. Linear trend analysis revealed no significant decline in manganese levels over time, suggesting that natural attenuation processes are insufficient to achieve compliance. These findings emphasize the urgent need for enhanced monitoring, source control measures and targeted remediation strategies to mitigate the environmental and public health risks posed by elevated Mn concentrations in the Kvirila River system.*

**Keywords:** mining, manganese, Kvirila River, Georgia, Zestaponi, Chiatura

## I. Introduction

Manganese (Mn) is a naturally occurring element commonly found in the Earth's crust and surface waters. While it is an essential micronutrient for biological systems at trace levels, elevated concentrations of manganese (Mn) in water bodies can pose significant risks to human health and aquatic ecosystems [1]. Elevated Manganese (Mn) levels that are often driven by anthropogenic activities such as mining and industrial discharge pose significant environmental and public health threats [2], [3]. In aquatic systems, manganese (Mn) exists in multiple redox states and interacts dynamically with other biogeochemical cycles, including those of iron (Fe), sulfur (S), and carbon (C), influencing nutrient availability, microbial community structures, and oxygen regimes [2], [4].

Long-term exposure to manganese (Mn), especially in drinking water, has been linked to neurodevelopmental effects in children and other health risks in vulnerable populations [11]. Consequently, many countries, including Georgia, have established strict regulatory thresholds for manganese (Mn) concentrations in water resources; in Georgia, the permissible limit is set at 0.1 mg/L.

In Georgia, the Black Sea Basin rivers, especially the Rioni and its tributary the Kvirila, are profoundly impacted by manganese (Mn) mining activities centered in the Chiatura region.

Historical and ongoing mining operations have led to the release of hundreds of thousands of tons of Manganese (Mn)-rich tailings into the river system annually [5]. These discharges result in widespread contamination of both water and sediments, which poses long-term ecological risks, including toxicity to aquatic life, bioaccumulation, and disruption of sediment-water interactions [5].

This study aims to assess the temporal and spatial patterns of manganese (Mn) concentrations in the Kvirila River over the period from 2017 to 2023. Utilizing official data provided by the National Environmental Agency (NEA) of Georgia, the study evaluates compliance with regulatory standards, identifies seasonal and annual trends, forecasts future concentration levels, and highlights areas requiring urgent environmental management interventions. By understanding the dynamics of manganese (Mn) contamination in the Kvirila river, this research seeks to support more effective policy responses and remediation strategies to protect public health and the environment.

Beyond local impacts, manganese (Mn) contamination intersects with broader environmental issues such as climate change. Rising global temperatures, altered precipitation regimes, and sea level rise are modifying hydrological processes, thereby intensifying manganese (Mn) mobilization and transport. For instance, increased storm intensity enhances erosion of manganese (Mn)-laden soils, while warming and hypoxic conditions favor the release of soluble manganese (Mn) from sediments [6]. This interaction not only exacerbates the spread of manganese (Mn) pollution, but also contributes to feedback loops in global carbon and nutrient cycles, with implications for greenhouse gas emissions and ecosystem resilience [7]. Climate-induced salinization and sea-level rise accelerate heavy metal release, particularly in coastal and estuarine environments [8] [9].

The Kvirila River Basin, located in western Georgia, is an area of particular concern for manganese (Mn) contamination due to its geological characteristics and extensive historical mining activities, especially around the cities of Chiatura and Zestaponi [5]. Chiatura is renowned for its manganese (Mn) ore deposits and has been a center of mining and industrial activity for over a century, contributing to elevated levels in nearby watercourses [5]. The environmental impact of such activities, combined with natural mineralization processes, makes the Kvirila River a critical focus for water quality monitoring and management efforts [5].

Mining and industrial discharge are the dominant drivers of manganese (Mn) pollution in polymetallic belts [10],[7], [11]. Given the scale and complexity of the issue, there is a critical need for interdisciplinary research that integrates geochemical analysis, ecological risk assessment, and climate science. This paper aims to evaluate the environmental risks associated with manganese (Mn) accumulation in Georgia's Black Sea Basin rivers using long-term monitoring data, pollutant modeling, and health risk indices. In doing so, it contributes to a broader understanding of how regional pollution challenges relate to global environmental implications.

## II. Methods

### 2.1. Study Area

This study focuses on the Kvirila River Basin, located in the western region of Georgia, specifically in the areas surrounding the cities of Zestaponi and Chiatura. The Kvirila River is a major tributary in the region, flowing through zones characterized by both natural mineral deposits and significant anthropogenic activities, particularly related to mining and industrial operations.

The majority of the manganese (Mn) concentration measurements were collected from the upper section of the Kvirila River near Zestaponi. This area is influenced by both natural geological formations rich in manganese (Mn) and the impacts of urban and industrial activities. Additionally, significant sampling and analysis were conducted at the lower section of the Kvirila River near Chiatura, a city historically known for its intensive manganese (Mn) mining and ore processing industries.

In both monitoring locations, manganese (Mn) concentrations frequently exceeded the national regulatory threshold of 0.1 mg/L. Exceedances were particularly prominent downstream of

Chiatura, reflecting the cumulative impact of industrial discharges and possible leaching from mining-related activities. The selected monitoring sites thus represent critical control points for understanding the spatial variability and severity of manganese (Mn) contamination within the Kvirila River system.

Due to the strategic environmental and economic relevance of the Kvirila River and its proximity to manganese (Mn) mining operations, this region serves as a valuable case study for evaluating interactions among natural mineralization, human activity, and water quality.

## 2.2. Data Source

The manganese (Mn) concentration data utilized in this study were obtained from the National Environmental Agency (NEA) of Georgia, accessible via <https://nea.gov.ge/>. The dataset comprised monthly maximum manganese (Mn) concentration measurements collected from January 2017 through December 2023. All concentration values were reported in milligrams per liter (mg/L) and reflect the highest recorded manganese (Mn) levels for each month within the respective year.

The data were sourced from official monitoring programs conducted by the NEA, which are designed to ensure compliance with national environmental standards and support the assessment of water quality trends across Georgia. According to national regulations, the permissible limit for manganese (Mn) concentration in water is 0.1 mg/L.

## 2.3. Data Processing

The raw dataset was structured into a matrix format with months as rows and years as columns. To facilitate analysis:

- The data were reshaped into a long-form structure to allow chronological ordering and time-series visualization.
- Months were treated as categorical variables to preserve the natural calendar order.
- Concentrations were evaluated against the regulatory limit to classify each monthly measurement as either compliant or non-compliant.
- Descriptive statistics, including annual averages and monthly trends, were calculated to assess the temporal distribution of manganese (Mn) concentrations.

## 2.4. Analytical Methods

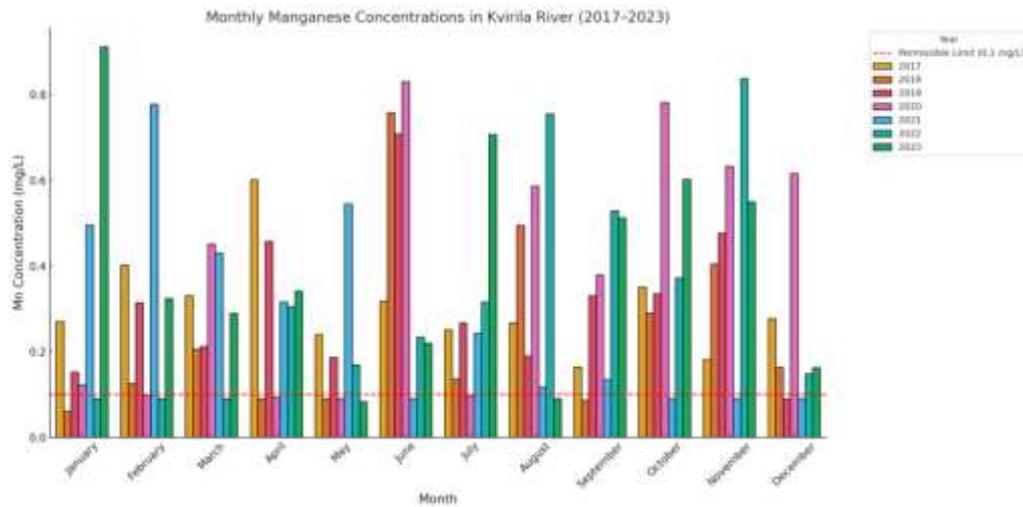
Several statistical and visualization techniques were employed:

- **Time-Series Plotting:** Monthly manganese (Mn) concentrations were plotted over time to visualize temporal patterns and highlight exceedances relative to the permissible limit.
- **Exceedance Analysis:** The number of months exceeding the regulatory threshold was calculated annually to evaluate compliance trends.
- **Heatmaps:** A heatmap was generated to visualize concentration intensities across different months and years.
- **Trend Forecasting:** A simple linear regression model was applied to annual mean concentrations to project future manganese (Mn) levels up to 2025 under the assumption of continued current conditions.

# III. Results

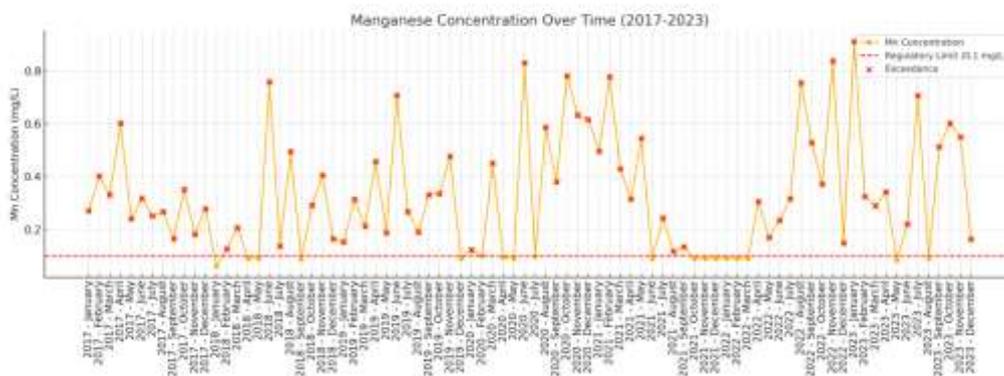
The comprehensive analysis of manganese (Mn) concentration data from 2017 to 2023 indicates persistent and widespread exceedances of the national regulatory threshold of 0.1 mg/L. Across the 84 monthly maximum concentration records, a total of 66 measurements (78.6%) surpassed the permissible limit. The year 2017 exhibited full non-compliance, with manganese (Mn) concentrations exceeding regulatory standards in all 12 months. Other years, including 2019, 2020,

and 2023, also showed elevated non-compliance rates, each recording exceedances in more than two-thirds of the monitored months (See Figure 1).



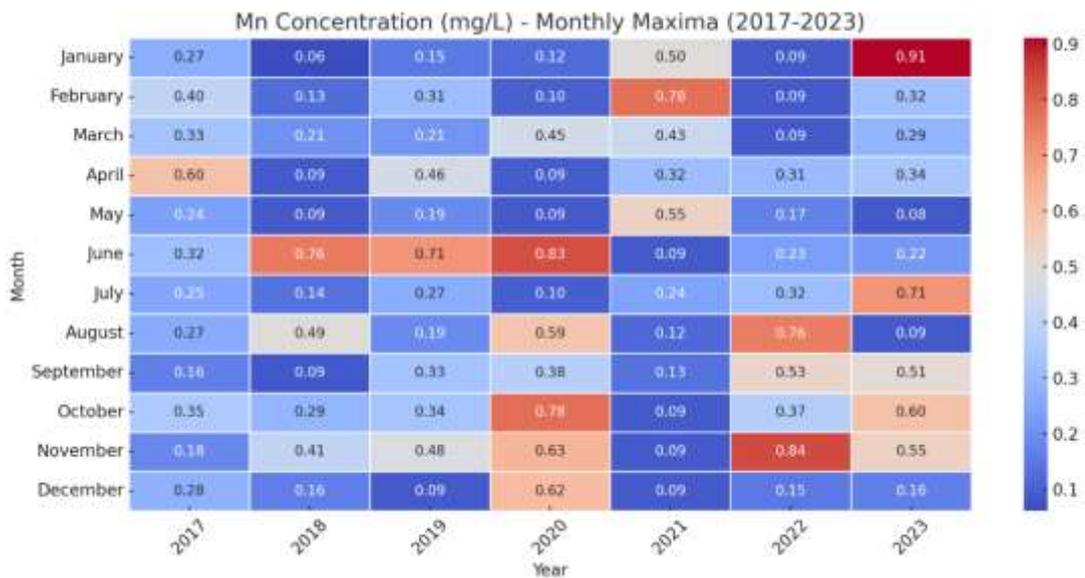
**Figure 1:** Combined monthly manganese (Mn) concentrations in the Koirila River from 2017 to 2023. Bars are grouped by month and color-coded by year. The red dashed line indicates the regulatory limit of 0.1 mg/L.

The annual mean manganese (Mn) concentrations reflected notable fluctuations over the observed period. Average concentrations were 0.305 mg/L in 2017, decreased slightly to 0.243 mg/L in 2018, and then rose again to 0.310 mg/L in 2019. The most pronounced peak was recorded in 2020, with an average concentration of 0.398 mg/L, followed by a minor decline in 2021 to 0.285 mg/L. A resurgence was observed in subsequent years, with 2022 and 2023 recording average concentrations of 0.328 mg/L and 0.400 mg/L, respectively. These results underscore persistent exceedances and a concerning upward trend in recent years, notably in 2020 and 2023 (Refer to Figure 2).



**Figure 2:** Monthly Manganese (Mn) Concentrations in the Koirila River Basin Compared to Regulatory Limit (2017–2023)

Monthly trends revealed consistent seasonal variations in manganese (Mn) levels. Elevated concentrations were most frequently observed during the summer and autumn months. June and November exhibited the highest average concentrations, each exceeding 0.45 mg/L, significantly surpassing the regulatory threshold. In contrast, May and December generally recorded lower manganese (Mn) concentrations; however, even during these months, exceedances were common, with four to five months per year still surpassing the permissible limit. This pattern suggests potential environmental or operational factors contributing to manganese (Mn) mobilization during specific periods of the year (Refer to Figure 3).



**Figure 3:** Heatmap of Monthly Maximum Manganese (Mn) Concentrations (mg/L) in the Kvirila River Basin (2017–2023)

Visualization through a heatmap of monthly data confirmed that high manganese (Mn) concentrations were not isolated events but were distributed consistently across months and years. Particularly noteworthy were the extreme values recorded in November 2020 and January 2023, with the latter reaching a peak concentration of 0.9114 mg/L – nearly nine times the regulatory limit. Analysis of exceedance frequency across individual months showed that March, June, July, August, September, October, and November had six exceedances out of seven years, corresponding to an exceedance rate of approximately 86%.

A linear regression model was applied to assess potential temporal trends in manganese (Mn) concentrations. The model indicated a weakly increasing trend in average manganese (Mn) concentrations over time, with predictions suggesting that, under current conditions, exceedances will persist at least through 2025. No statistically significant declining trend was observed, emphasizing that manganese (Mn) levels are unlikely to improve without deliberate intervention.

In summary, the dataset reveals a severe and persistent manganese (Mn) contamination issue within the monitored system. The high frequency of exceedances across years and months, coupled with increasing average concentrations in recent years, indicates that natural attenuation or incidental improvements are insufficient to achieve compliance. The results strongly highlight the necessity for immediate and sustained remediation efforts, improved monitoring practices, and further investigation into the underlying causes of seasonal variability to develop effective management strategies.

#### IV. Discussion

Elevated manganese (Mn) levels in Georgian rivers are predominantly due to mining operations lacking adequate environmental monitoring [5]. Redox-sensitive manganese (Mn) cycling, driven by hydrological variability and sediment dynamics, facilitates its mobility and bioavailability [2]. Once mobilized, manganese (Mn) alters aquatic redox conditions, displaces other trace metals, and supports eutrophic conditions through phosphorus mobilization [2].

The ecological consequences are severe. Manganese (Mn) affects aquatic organisms at sub-lethal levels, impairing growth and reproduction, as demonstrated by studies in the Selangor and Barnoi rivers [6], [8]. Long-term exposure to manganese (Mn) has been associated with neurological

deficits in fish and biomagnification up the food web [1]. Health risk modeling in this study corroborates similar findings in China [10].

Climate variability acts as a critical modifier of manganese (Mn) risk. Rising temperatures enhance microbial manganese (Mn) cycling, while extreme rainfall accelerates erosion and runoff [6]. Sea-level rise and saline intrusion, particularly in the Rioni river, may shift sediment redox profiles and promote manganese (Mn) release [9]. Integrating climate factors into heavy metal contamination environmental risk assessment frameworks is crucial for anticipating future risks [9].

The results of the temporal analysis highlight a significant and persistent manganese (Mn) contamination problem that poses substantial regulatory and environmental challenges. The exceedance of the national permissible limit of 0.1 mg/L in nearly 80% of the recorded observations between 2017 and 2023 indicates systemic issues rather than isolated or anomalous events. The particularly high levels recorded in 2020 and 2023, coupled with the absence of any clear declining trend, suggest that natural attenuation processes are ineffective in this system or that external inputs of manganese (Mn) continue unabated.

Various environmental and operational factors likely contribute to the seasonal and annual fluctuations observed in manganese (Mn) concentrations. Elevated levels during the summer and autumn months could be attributed to increased temperatures, which enhance the microbial activity responsible for manganese (Mn) mobilization from sediments. Additionally, periods of high rainfall during late spring and early summer may facilitate the leaching of manganese (Mn) from soils into groundwater and surface water systems, contributing to elevated concentrations. In contrast, lower concentrations in winter months such as December may reflect reduced microbial activity, lower rates of geochemical weathering, and diminished hydrological transport processes.

The extremely high peak concentration recorded in January 2023 (0.9114 mg/L) suggests the possibility of point source pollution events, such as industrial discharges, mining activities, or failures in water treatment processes. Although background geochemical conditions can sustain elevated manganese (Mn) levels naturally, such acute spikes are often indicative of anthropogenic influences. Therefore, a more detailed investigation into potential local sources of manganese (Mn) contamination is warranted.

Chronic exceedances of manganese (Mn) present serious implications for public health and ecological stability. Elevated manganese (Mn) concentrations in drinking water are associated with neurological effects, particularly in children, while aquatic ecosystems can suffer from altered species compositions and reduced biodiversity [8]. Given these risks, the current trends represent not only a regulatory compliance issue but also a broader environmental and public health concern.

Given the absence of natural recovery trends, proactive intervention is necessary. Potential mitigation measures include:

- Enhanced water treatment technologies such as oxidation-filtration, ion exchange, or biological filtration systems specifically targeting manganese (Mn) removal.
- Source control strategies, including the regulation and monitoring of industrial discharges.
- Restoration of natural hydrological conditions to stabilize redox environments and minimize manganese (Mn) mobilization.
- Seasonal monitoring adjustments to better capture peak concentration periods and inform management decisions.

In conclusion, the evidence strongly supports the need for immediate, comprehensive, and sustained action to address manganese (Mn) contamination. Future studies should focus on identifying specific contamination sources, understanding seasonal geochemical dynamics, and assessing the effectiveness of mitigation efforts through adaptive monitoring frameworks.

## V. Conclusion

Manganese (Mn) accumulation in Georgia's Black Sea Basin rivers is a multi-dimensional environmental challenge, driven by industrial, geochemical, and climatic processes [5], [9]. Its impacts on aquatic ecosystems, public health, and climate feedbacks necessitate immediate intervention [7].

Mitigation strategies should include microbial-induced calcite precipitation, phytoremediation, and sediment dredging in hotspots [6]. Implementation of real-time monitoring technologies and data-driven public health advisories is essential [3]. At the policy level, Georgia should align its water management framework with EU directives and collaborate regionally to address transboundary pollution [11].

An interdisciplinary approach combining environmental science, public health, and policy is critical to managing manganese (Mn) pollution sustainably [7]. Future research should focus on temporal monitoring, advanced remediation technologies, and socioeconomic risk communication [1].

The comprehensive analysis of manganese (Mn) concentration data from 2017 to 2023 clearly demonstrates a persistent and significant pattern of non-compliance with the national regulatory limit of 0.1 mg/L. Nearly 80% of monthly maximum measurements exceeded the permissible level, with certain years, notably 2017 and 2023, showing particularly widespread exceedances. Seasonal trends indicated that manganese (Mn) concentrations typically peak during the warmer months, suggesting environmental factors such as temperature-driven redox reactions and hydrological dynamics may play a critical role in manganese (Mn) mobilization.

The increasing trend in annual average concentrations, especially in recent years, highlights an urgent need for intervention. Forecasting analysis suggests that, without targeted remediation, manganese (Mn) levels will continue to exceed regulatory limits in the coming years. The sporadic occurrence of extremely high concentrations further suggests the potential influence of anthropogenic activities, warranting more detailed investigation into possible industrial or land-use sources.

Given the human health and ecological risks associated with elevated manganese (Mn) levels, immediate and sustained management actions are necessary. Future efforts should prioritize source identification, seasonal monitoring enhancements, and the implementation of effective treatment technologies to ensure both regulatory compliance and the protection of public health and the environment.

Ultimately, managing manganese (Mn) contamination demands an interdisciplinary approach that integrates environmental science, public health, and policy. Future research should prioritize the identification of pollution sources, the refinement of remediation strategies, and the development of adaptive monitoring frameworks to ensure long-term water safety and ecosystem resilience.

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