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Denyse Joy Mukabayizere[1], Dr. Martin Vincent Nsanzumukiza[1], Euphrosine Muyizere[1], Joseph Singirankabo[1]

[1]Faculty of Environmental Studies, Department of Environmental Economics and Natural Resource Management University of Lay Adventists of Kigali (UNILAK), Kigali, Rwanda

Email of main author: **kadenyjoy@gmail.com**

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Abstract

This study assessed the impact of mining activities on water quality in the Nyakabingo stream and Nyabarongo River in Rwanda's Rulindo District. It involved laboratory analysis of physicochemical parameters such as EC, turbidity, TDS, TSS, pH, nitrate, sulphate, and heavy metals (Al, As, Fe, Cd, Cu, Cr, Mn, Pb). Water samples were collected from untreated mining wastewater, treated wastewater, and upstream and downstream points of the river. Descriptive methods including documentary review, site observation, and interviews were used to understand mining practices. The results obtained for pH, heavy metals namely Mn, Cd, Pb, Cu, Fe obtained at the mining site and wastewater discharged from the treatment dams into Nyakabingo stream were not compliant to the requirements specified in RS EAS 1172:2014, the national standard on wastewater discharged on land and into water bodies. This also aligns with elevated levels for EC and TDS. In contrast, lower values complying to the requirements specified in RS 564: 2023 on specifications of ambient water, were obtained at upstream and downstream points on Nyabarongo river due to the long distance and the presence of streams that dilute the river water resulting in reduced concentration. This implies that the closer the water body is to the point of wastewater discharge, the more polluted it gets. The results have also indicated that the established treatment dams only helped to reduce the total suspended solids discharged in the environment while the level of chemical pollutants remained elevated. The mining company should engage in further treatment of the wastewater prior to discharge into the environment to ensure pollutants in the wastewater discharged to not exceed tolerable limits on the applicable national standards.

Key words : *Mining Activities, Acid Mine Drainage, Standard Compliance, Water Quality, Chemical Polluants*

1. Introduction

Rivers are vital ecosystems that provide essential services, including potable water when treated, agricultural irrigation and habitats for diverse aquatic life (Apostolaki et al., 2020). However, river quality is affected by different anthropogenic activities such as mining, agriculture, industrial discharges and improper waste disposal, which introduce pollutants like heavy metals, nutrients, and sediments into water bodies, thereby altering their chemical, physical and biological characteristics (Zhou et al.; 2022). Mining activities have increasingly compromised river water quality worldwide, leading to significant ecological and public health concerns (Ouma et al., 2022). The extraction and processing of minerals often result in the release of pollutants, such as heavy metals and sediments, into adjacent water bodies (Timothy & Williams, 2019). These contaminants can persist in the environment, affecting water quality, aquatic organisms and human health. Excessive concentrations of these metals can lead to bioaccumulation in the food chain, affecting both the ecosystem and the health of communities who consume contaminated fish or use polluted water for domestic purposes. Mudenda, (2022). Furthermore, mining waste, including tailings and chemicals used in mineral processing, can be released into the water systems, increasing the negative impacts on water quality (Wolkersdorfer & Mugova, 2022).

Different minerals are being extracted including wolframite. Acid mine drainage has been reported as the major environmental concern in tungsten mining regions. Sulfide-bearing minerals in tungsten ore react with air and water to generate sulfuric acid (H_2SO_4) (Simate & Ndlovu, 2014). This acidic runoff dissolves toxic metals and lowers the water pH and pollutants introduced in water sources lead to water contamination (Han et al., 2021). Local populations in Africa have been vulnerable to the negative impacts of mining contamination on agriculture, public health and the environment due to economic pressures and a slower rate of environmental awareness development (Okereafor et al., 2020).

In this regard, this study was conducted to assess the water quality of Nyakabingo stream and Nyabarongo River, located in Shyorongi, Rulindo District due to wolfram mining activities. This river is adjacent to active mining sites, making it susceptible to pollution, which may affect its use as source of water used for agricultural activities. Assessing the river's water quality is essential to understanding the impacts of these mining activities and establishing a baseline for future environmental protection efforts to ensure proper management of water resources for current and future generations.

1.1. Objectives of the Study

1.1.1 The general objective

The general objective of this study was to evaluate the impacts of mining activities on water quality focusing on Nyakabingo stream and Nyabarongo River located in Shyorongi, Rulindo district, Northern Province of Rwanda.

1.1.2 Specific objectives

This study focused on the following specific objectives:

(i) To assess the mining activities applied in Nyakabingo
(ii) To determine the physicochemical properties of the surface water discharged from the mining site, treatment dams to Nyakabingo stream, at upstream and downstream points on Nyabarongo river;
(iii) To determine the relationship between mining activities and Nyakabingo stream and Nyabarongo river water quality

2. Materials and methods

2.1 Profile of Rulindo district

Rulindo district is one of the five districts of the Northern province. Rulindo District is administratively divided into 17 sectors as shown in figure 3.1, which, in turn, are also divided into cells and villages. Its surface area is estimated at 567 square kilometers (km^2). This district is mountainous containing Tare (more commonly known as Nyirangarama), Tumba and Cyungo mounts with altitude reaching 2,438 m. These mounts are interspersed with valleys and swamps. It has a tropical climate, characterized by a succession of rainy and dry seasons. The average annual temperature is 19 °C. High temperatures are observed can reach 28 °C. Rainfall normally reaches 1,243.3 mm per year on average. The recent 5th Rwanda Population and Housing Census (PHC5) conducted by the National Institute of Statistics of Rwanda (NISR) in 2022 revealed that Rulindo district is the least populated district in the Northern Province with 360,144 inhabitants, consisting of 171,849 males and 188,295 females. This corresponds to 17.7% of the total resident population of Northern Province. In Rulindo district, crop farming and animal husbandly are on large scale. Agricultural households represent 83.9% with 79.3% of households engaged in crop farming and 66.3% in livestock husbandry. This implies that water resources should be protected from contamination to ensure it will still fit its use for agricultural products. Other economic activities include wolfram/tungsten mining performed in Syorongi Sector by Trinity Metals- Nyakabingo Mine Limited.

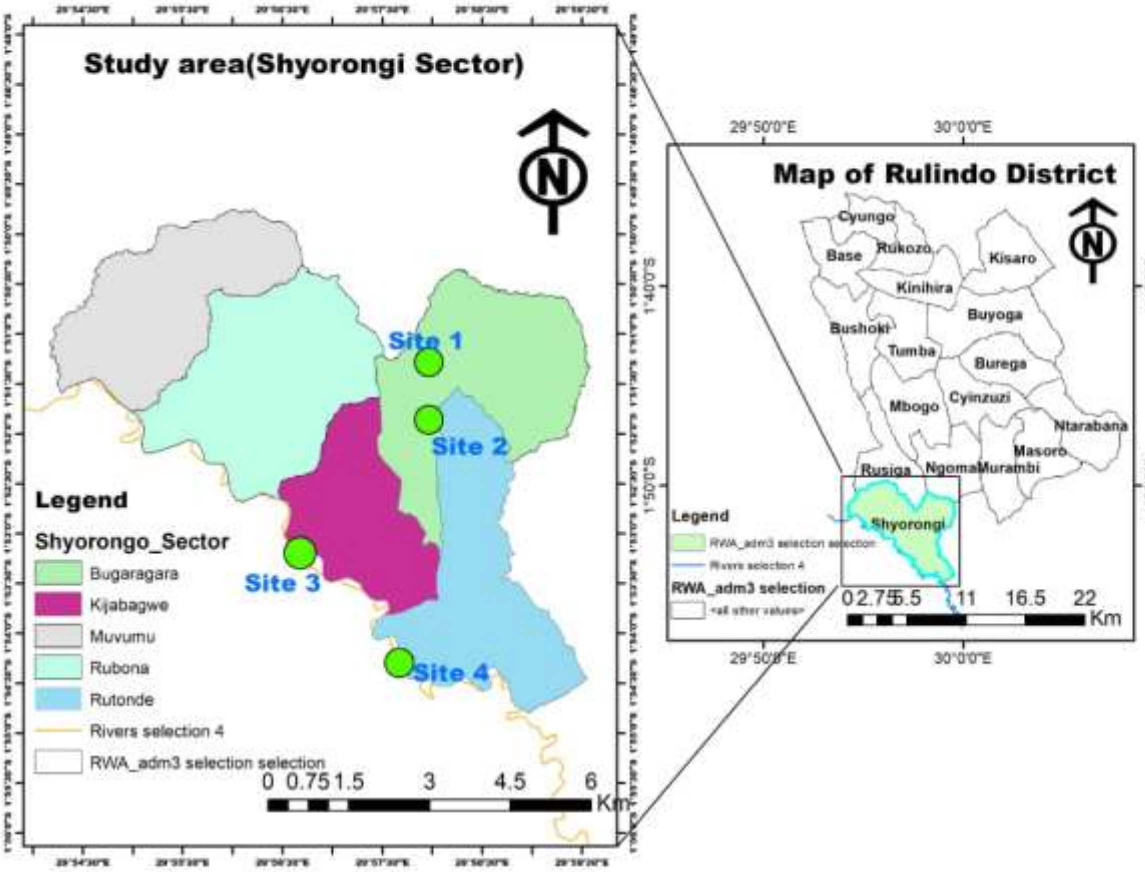

Figure 3-1: Map of the study area

2.2 Research design and sampling techniques

This study adopted different research designs to cater for both independent and dependent variables. The descriptive research design was applied to gather information related to mining activities while laboratory experimental were design and conducted to evaluate the physicochemical properties of wastewater from the mining site (site 1), wastewater released into Nyakabingo stream from the treatment dams (site 2), surface water from the upstream and downstream points on Nyabarongo river (site 3 and site 4, respectively.

To obtain the data related to mining activities, the research involved site observation, documentary review and interview. To evaluate the physicochemical properties, water samples were collected from the mining site, wastewater released into Nyakabingo stream from the treatment dams, surface water from the upstream and downstream points on Nyabarongo river.

The sample size was determined as specified in ISO 5667-10: 2020.

Experiments were carried out to quantify different physicochemical parameters. To assess the compliance status, test results were compared with the requirements provided in the national standards. For wastewater discharge (site 1 and site 2), the applicable national standard is RS EAS 1172: 2024, a standard that provides requirements on wastewater discharged on land and into water bodies while RS 564: 2023 on ambient water specifications applies to surface water collected at upstream and downstream points on Nyabarongo river (site 3 and site 4).

To ensure representation of different segments of the river namely upstream, midstream near mining operations and downstream and that the data reflects the variability that may occur in the physicochemical characteristics of water throughout the river, stratified sampling technique applied. Water samples were collected from each stratum using an equal sampling approach whereby an equal number of samples (4 samples) was collected from each stratum. By analyzing the results from each stratum separately, it became possible to identify patterns of contamination specific to areas influenced by mining, forming a basis while formulating appropriate mitigation measures. Before collecting samples, the required equipment including glass bottles, gloves, labels and collers with ice packs for transportation were gathered. Sampling bottles were then pre-cleaned with deionized water to prevent contamination.

At each designated sampling point, the clean sample bottles were rinsed three times with sampled water from the river and the rinsed bottles were submerged about 10–15 cm below the water surface to avoid collecting surface debris. Aeration during sampling, touching the inside of the bottle or lid were also be avoided to prevent contamination. Each sample was labelled with unique identification number.

After sample collection, immediate preservation in coolers with ice packs was necessary to ensure physicochemical characteristics of sampled water are not affected during transport. Collected samples were transported to the laboratory within 24 hours and upon arrival at the laboratory, the samples were logged into the laboratory's system and checked to ensure they are in good condition and were then refrigerated at 4^0C to prevent any changes to the chemical and physical characteristics of the water quality.

Different physicochemical parameters have been tested following the procedures detailed in the table below:

Table 3-1: Test methods used for different physicochemical parameters

Parameter	**Analytical method**	**Reference test method with detailed procedure**
Ph	Potentiometric	ISO 10523
(EC, µS/cm	Electrometric method	ISO 7888
Turbidity	Nephelometric method	ISO 7027-1
TDS	Electrometric method	ASTM D5907-13
TSS	Gravimetric method	ISO 11923
Sulphate	Turbidimetric method	ISO 15923-1
heavy metals	Spectrophotometric method	ISO 11885

3. Results and Discussion

3.1. Indicators related to mining activities

3.1.1. Mining method used for ore extraction

The mining operations at Nyakabingo Mine are predominantly carried out using the underground mining method. This process starts with exploration and drills to wolfram body, followed by the establishment of access tunnels and shafts to reach the ore deposit.

Figure 3-1: Underground mining at Trinity metals-Nyakabingo mine

Source: Field survey, 2025

Once the ores are accessed, miners use drills and blasting techniques. The ores are then transported to the surface for processing. The efficiency of this method is linked with mechanization. In addition, the use of high-capacity drilling and blasting enable them to extract significant amounts of ores. This method is preferred due to its relative safety, ability to reach deep ore bodies, minimized surface disruption and reduced excessive water runoff and it also generates less dust and noise pollution. This makes it more compatible with the surrounding communities. Despite the above-mentioned advantages, underground mining of wolfram can disrupt groundwater systems through acid mine drainage or heavy metal leaching. It was also observed that the disposal of tailings and waste rock presents another challenge, as improper handling can lead to long-term soil and water pollution due to heavy metals leaching.

Furthermore, onsite observation indicated that the excavation of underground tunnels generates large quantities of waste rock, deposited in stockpiles near the mining site. Without proper containment or vegetation cover, these waste dumps become highly susceptible to erosion, especially during heavy rainfall events. Rainwater can then wash away fine soil particles and loose materials from the mining site, carrying them downhill toward Nyakabingo stream. This may result in increased turbidity and pollutants in the water bodies. Additionally, access roads and mining facilities required land clearing and leveling, contributed to surface instability, increasing the likelihood of soil displacement. In case of heavy rain, eroded material can enter the Nyakabingo stream and other nearby water bodies, leading to water quality degradation and local ecosystems disruption. Furthermore, sediment deposition can contribute to the narrowing of the Nyakabingo stream channels, increasing the risk of flooding during rainy seasons. To overcome this environmental issue, the company has engaged in trees plantation and established the dams where mining residues, fine soils and rocks particles accumulate reducing sedimentation in the Nyakabingo stream.

Figure 3-1: Trees plantation to prevent soil erosion

Source: Field survey, 2025

(A) Plant cleared due to mining activities that would contribute to soil erosion during the rainy season. (B) Trees plantation in the surrounding to prevent soil erosion (C)Trees plantation around the treatment dams to prevent direct discharge of wastewater into the environment.

3.1.2. Scale of mining activities

Through a documentary review of detailed production logs and quarterly performance reports, it has been confirmed that the underground wolfram mining operation is functioning at a higher production scale. As per the publication titled Creating Critical Excellence in Rwandan by Trinity metals of December 2023, the production of wolfram was forecasted as presented in figure 3.1 below.

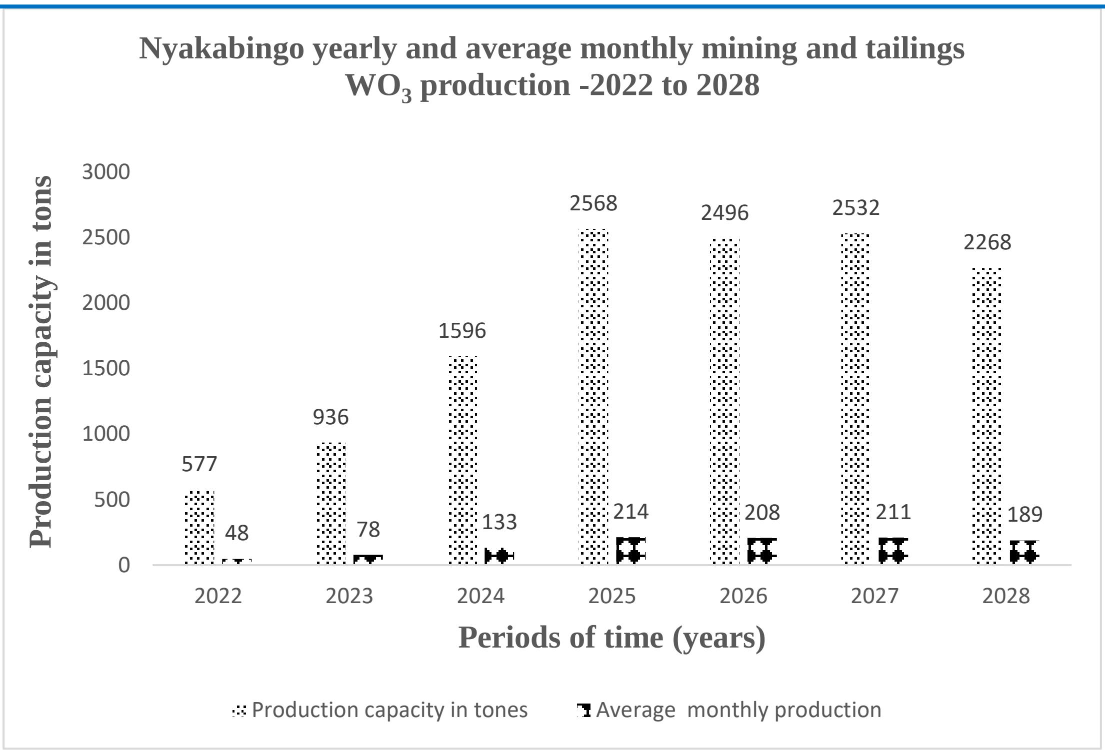

Figure 3-2: Nyakabingo yearly and average monthly mining and tailings WO_3 production -2022 to 2028

This is aligned with the Mining Rwanda's mineral export earnings surge issued by Rwanda Mines, Petroleum and Gas Board (RMB).

Compared to the previous years, the production capacity of wolframite is forecasted to increase. This increase is attributed to different driving factors. Firstly, the Rwandan government has actively encouraged investment in the mining sector through the implementation of policies that encourage both domestic and foreign participation.

Secondly, the rising demand for tungsten in various industries has supported Rwanda's export volumes. Additionally, illegal miners are being sensitized on the negative consequences of the activities they are undertaking and it is expected that by all of them will be hired by Trinity metals to continue the journey of extracting wolfram legally. As per figure 3.2, by 2028 the wolfram production is expected to start decreasing since the ores are non-renewable and will be depleting. For the company to remain operational and sustain supply, it will open up new mining areas to expand the mine and exploit secondary sources such as scrap metal and end-of-life tungsten products.

3.1.3. Distance of mining operations from the Nyakabingo stream and Nyabarongo river

From the site observation, wastewater from the treatment dams is directly discharged to the Nyakabingo stream located at around 100 meters from the treatment dams. The proximity of the mining site suggests a high risk of pollutants being discharged into the Nyakabingo stream. These pollutants result from different mining activities undertaken including ore crushing and mineral processing. Wastewater from mineral processing, often containing residual chemicals, heavy metals ions and suspended solids, was observed near the site. Additionally, tailings disposal sites are located within 100 meters of the stream, increasing the likelihood of leakage into surface and groundwater. Similar trends have been reported in other tungsten mining regions, where proximity to water bodies has led to elevated metal concentrations and altered physicochemical parameters (Vergilio et al., 2021).

Lastly, the distance from the mining site and Nyabarongo river upstream and downstream was considered to be able to assess the impacts of mining activities on Nyabarongo river quality. It was noted that Nyakabingo mining site, specifically where the discharge of wastewater is takes place is located at approximately 40 km from the Nyabarongo river.

3.1.4. Discharge of untreated wastewater

One of the primary sources of wastewater in underground wolfram mining at Nyakabingo is mine dewatering, which involves pumping out groundwater that leaks into mining tunnels and shafts. This water often carries dissolved metals and suspended solids.

Furthermore, during ore processing, significant wastewater is generated from crushing, grinding and mineral concentration processes. For these processes, large volume of water is required, which in turn, become contaminated with fine ore particles, reagents and residual processing chemicals such as flotation agents and pH modifiers. As a result, the turbidity of water increases and chemical contamination in receiving water bodies. Improper discharge of processing wastewater can result in sediment deposition and toxic effects on aquatic ecosystems (Babuji et al., 2023).

Another source of wastewater comes from tailings storage facilities. From these storage, heavy metals and processing chemicals can leach into groundwater or be carried into surface water through leakage or accidental spills. Also, precipitation and surface runoff can transport contaminants from tailings dumps into nearby Nyakabingo stream.

Through the site observation, it was noted that the mining company has established treatment dams in which wastewaters undergo decantation to separate the solid waters allowing clear wastewater to be discharged in the environment. This treatment done is not effective as it will not prevent the transport of dissolved ions including heavy metals. As a result, the surrounding water is contaminated with soluble chemical pollutants.

3.1.5. Release of tailings or effluents into the river

Wolfram ore beneficiation is the most significant source of tailings and effluents. This process typically involves crushing, grinding and gravity separation techniques, which generate fine-grained tailings composed of residual minerals, chemical reagents and heavy metals. Another contributor to effluents is acid mine drainage (AMD). This acidic runoff dissolves heavy metals from surrounding rocks, increasing their mobility and leading to long-term pollution of the river system (Punia & Singh, 2021). In addition, water used for ore washing and separation often contains fine sediments, residual chemicals and elevated metal concentrations.

In a group discussion, which included environmental officers, mining engineers and tunnels supervisors, it was observed that tailings generated are collected and effluents from the mining site are channeled in a pipe that transport them to the treatment dams, established to reduce suspended solids that would be discharged into the environment. The contribution of this treatment dams is acknowledged. However, there is a need to explore other means to ensure heavy metals are also removed from wastewater before it is discharged into the Nyakabingo steam. The established treatment dams are presented in figure 3-3 below.

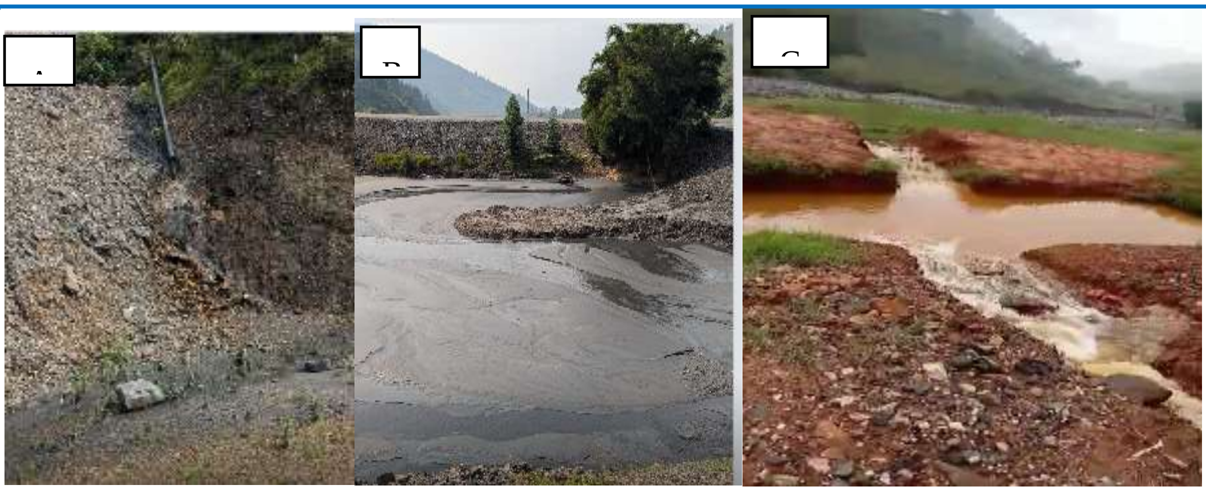

Figure 3-2: Decantation of wastewater from the mining site

Source: Field survey, 2025

(A)Wastewater discharged from the mining site channeled into the pipe to avoid the direct release of wastewater into the environment, (B) Discharged wastewater enters the treatment where decantation takes place (C) Wastewater leaving the last treatment dams to the environment with reduced turbidity

From this figure 3-2, it is clear that water leaving the mining site and the first treatment dam has higher turbidity expressed by the dark grey colour. After decantation, total suspended solids were left out leading to a decreased turbidity for water released into the Nyakabingo stream leaving from the last treatment dam.

3.2.Physicochemical properties of the Nyakabingo stream and Nyabarongo river

Water samples were collected from the following sites:

Site 1 – Untreated wastewater directly from the mining site

Site 2 – Wastewater treated in dams before discharge into Nyakabingo stream

Site 3 – Nyabarongo upstream (reference site, before mining impact)

Site 4 – Nyabarongo downstream (after mixing with mining wastewater)

3.2.1. Electrical conductivity (EC)

The results obtained for Electrical conductivity at the four sampling sites considered in this study are presented in Table 3-1:

Table 3-1: Variation of electrical conductivity across sampling sites

Parameter	**Sampling site**	**Mean and standard deviation**	**National Standard requirement**	
Electrical Conductivity in mS/m at 25°C	Site 1	58.23±34.75	250	RS EAS 1172: 2024
	Site 2	148.5±80.80		
	Site 3	17.815±4.23	100	RS 564: 2023
	Site 4	16.758±3.78		

Electrical conductivity (EC) measurements serve as an indicator of dissolved ions in water.

The mean EC value at the mining site (58.23±34.75 mS/m) is higher than the upstream Nyabarongo measurements (17.815±4.23 mS/m), suggesting contamination by dissolved minerals and metal ions released during mining and ore processing. The treatment dams exhibit even higher EC values, with a peak of 205 mS/m recorded in July 2024 for wastewater discharged from the treatment dams. This suggests that mining effluents contain high concentrations of dissolved solids due to their accumulation overtime. However, downstream EC levels (16.758±3.78 mS/m) remain close to upstream values, implying some degree of natural dilution of the river water. Furthermore, when compared to the requirements of applicable Rwanda standards, all the values of EC obtained comply with the standard requirements, i.e. 250mS/m for wastewater to be discharged into water bodies and 100mS/m for ambient water. While the treatment dams help reduce some contamination before discharge into the river, the high EC values recorded within the dams (mean 148.5±80.80 mS/m) suggest that further optimization of treatment processes and regular monitoring of EC are necessary.

3.2.2. Total dissolved solids (TDS)

The results obtained for TDS at the four sampling sites considered in this study are presented in Table 3-2:

Table 3-2: Variation of TDS across sampling sites

Parameter	**Sampling site**	**Mean and standard deviation**	**National Standard requirement**	
Total Dissolved Solids at 180°C, in mg/L	Site 1	395.083±195.55	1500, max	RS EAS 1172: 2024
	Site 2	1412.125±279.04		
	Site 3	130.31±31.80	Not covered	RS 564: 2023
	Site 4	133.38±38.77		

As per Table 3-2 above, TDS values at the mining site show a mean concentration of 395.083±195.55 mg/L, which is higher than upstream levels (130.31±31.80 mg/L), suggesting that mining processes contribute to an increased load of dissolved minerals in the water. The highest TDS levels were recorded in the treatment dams, with an average of 1412.125±279.04 mg/L, peaking at 1690.5 mg/L in January 2025 at the treatment dam.

This implies that wastewater from the mining process contain high concentrations of dissolved materials, due to leaching of minerals and chemical residues from ore processing. At the downstream location on Nyabarongo river, TDS levels (133.38±38.77 mg/L) are close to upstream values, indicating that natural dilution has occurred due to the presence of streams in the surrounding environment. Given that TDS concentrations in the treatment dams are far above natural river levels, additional interventions are required to enhance water quality management.

3.2.3. Total suspended solids (TSS)

The results obtained for TSS at the four sampling sites considered in this study are presented in Table 3-3 below:

Table 3-1Variation of TSS across sampling sites

Parameter	**Sampling site**	**Mean and standard deviation**	**National Standard requirement**	
TSS at 105°C, in mg/L	Site 1	726.2±834.54	80 mg/L, max	RS EAS 1172: 2024
	Site 2	29±20.22		
	Site 3	822.6±422.56	2100 mg/L, max	RS 564: 2023
	Site 4	1170.75±293.30		

The data presented in table 3-3 indicate that the highest TSS concentration recorded was from the mining site in July 2023 (2178 mg/L). At this sampling site, the data exceeded the national standard requirement of 80 mg/L for mining sites, indicating a serious impact of mining activities on water quality. The treatment dams exhibited much lower TSS values, with a mean of 29 mg/L, which complies with applicable national standard requirements. Lower values of TSS were recorded for wastewaters from the treatment dams as a result of decantation which allowed solid particles to settle at the bottom and clearer water to be separated from the sediments. Upstream and downstream values showed considerable variation, with the highest concentration observed downstream (1170.75±293.30 mg/L). The overall mean TSS values at the mining site (726.2±834.54 mg/L) still greatly exceeded the national standard, emphasizing the need for strict environmental controls at the mining site.

3.2.3.1.Turbidity

The results obtained for turbidity at the four sampling sites considered in this study are presented in Table 3-4 below:

Table 3-2: Variation of turbidity across the sampling sites

Parameter		**Jan-25**	**National Standard requirement**	
Turbidity, NTU	Site 1	Out of the range	30 NTU, max	RS EAS 1172: 2024
	Site 2	163.50		
	Site 3	309.50	Not covered by the standard	RS 564: 2023
	Site 4	417.00		

The results presented in Table 3-4 indicate a significant variation in turbidity levels across different locations in the Nyakabingo stream during January 2025. At the mining site, turbidity values exceeded the detection limits and hence reported as out of the range. This is due to many suspended solids resulting from mining operations especially the ore washing and processing and also from the underground mine discharges. The turbidity at the treatment dams is recorded at 163.50 NTU, indicating a reduction in turbidity post-treatment but still exceeding typical water quality standards of 30 NTU as per RS EAS 1172:2024. Upstream of the river, the turbidity level is 309.50 NTU and downstream, it rises to 417.00 NTU. This trend suggests that mining activities are contributing to an increase in sedimentation and pollutants in the water.

3.2.4. Chemical parameters

This section presents the results of chemical parameters tested namely pH, SO_4^{2-}, NO_3^-, Al, As, Cd, Cr, Pb, Fe, Mn and Cu.

3.2.4.1.pH

The results obtained for pH at the four sampling sites considered in this study are presented in Table 3-5 below:

Table 3-3: Variation of pH across sampling sites

Parameter	**Sampling site**	**Mean and standard deviation**	**National Standard requirement**	
pH at 25°C	Site 1	3.67±0.436	5-9	RS EAS 1172: 2024
	Site 2	2.6±0		
	Site 3	7.23±0.30	5.5-8.5	RS 564: 2023
	Site 4	7.34±0.33		

The results in Table 3-5 indicate that the pH values at the mining site, with readings ranging from 3.3 to 4.3 are not compliant as they consistently fall below the national standard range of 5-9 (RS EAS 1172: 2024), This suggests significant acidification, potentially linked to the mining activities, which are known to contribute to the leaching of acidic compounds into the surrounding environment. For the treatment dams, the pH of 2.6 was maintained constant and it is far below the national standard, indicating insufficient treatment or lack of effective neutralization measures. In contrast, the pH levels at upstream and downstream points on Nyabarongo river were within the standard limits of 5.5-8.5 (RS 564: 2023), with upstream values showing a mean of 7.23 and downstream values also hovering around 7.3. This suggests that, Nyabarongo river water quality remains relatively unaffected by the mining site due to the long distance and the dilution by the surrounding streams. The non-compliance of the mining site and treatment dams to the national standard emphasizes the need for improved adherence to the national environmental regulations and standards and the implementation of more effective water treatment processes.

3.2.4.2.Sulphate ions concentration

The results obtained for sulphate ions concentration at the four sampling sites considered in this study are presented in Table 3-6 below:

Table 3-4: Variation of sulphate ions concentration across sampling sites

Parameter	**Sampling site**	**Mean and standard deviation**	**National Standard requirement**	
Sulphate ions in mg/L	Site 1	122.6±29.48	500, max	RS EAS 1172: 2024
	Site 2	725.33±143.057		
	Site 3	4.6±3.43	600, max	RS 564: 2023
	Site 4	3.5±2.38		

The data from the sampling sites as shown in the table 3-6 above, reflect variations in sulphate ion concentrations. At the mining site, there is an increasing concentrations of sulphate ions, with values ranging from 76 mg/L in July 2023 to 135 mg/L in July 2024, with a mean of 122.6 mg/L (±29.48). These values indicate a general compliance to the national standard acceptable limit of 500 mg/L specified in RS EAS 1172: 2024. In contrast, the treatment dams show higher concentrations, changing from 580 mg/L in November 2023 to 866 mg/L in January 2024, resulting in a mean of 725.33 mg/L (±143.06), which greatly exceeds the national standard. The sharp increase in sulphate ion concentrations in the treatment dams could be attributed to insufficient treatment efficiency or inadequate management of the dam water quality. The samples collected at upstream point on Nyabarongo river of the mining site show relatively low concentrations, averaging 4.6 mg/L (±3.43), well within the permissible limit of 600 mg/L as per RS 564: 2023. Downstream, the sulphate concentration also remains low, with a mean of 3.5 mg/L (±2.38), indicating minimal contamination. The non-compliance at the treatment dams is possibly due to high concentrations of waste or ineffective treatment systems.

3.2.3.3 Nitrate ions concentration

The results obtained for nitrate ions concentration at the four sampling sites considered in this study are presented in Table 3-7 below:

Table 3-5: Variation of nitrate ions concentration across sampling sites

Parameter	Sampling site	Mean and standard deviation	National Standard requirement	
Nitrate ions in mg/L	Site 1	5.06±0.73	10, max	RS EAS 1172: 2024
	Site 2	15±1		
	Site 3	1.52±0.57	10, max	RS 564: 2023
	Site 4	1.775±0.50		

The results presented in table 3-7 above indicate that at the mining site, the nitrate concentration varies between 4.2 mg/L and 6.1 mg/L, with an average of 5.06±0.73 mg/L, which shows compliance to the national standard limit of 10 mg/L (RS EAS 1172: 2024). However, wastewater discharged from the treatment dam to the environment is not compliant as the minimum (14 mg/L) and maximum (16 mg/L) values obtained exceeded the requirement specified in RS 564:2023 (10 mg/L), suggesting potential issue in the treatment process. For other three sampling sites under consideration, there test results obtained comply with the standard requirement. The lowest values of nitrate ions concentration are recorded for surface water collected upstream and downstream on Nyabarongo river. At these upstream and downstream points, the nitrate concentrations vary within the lower range, from 1.0 mg/L to 2.4 mg/L, with means of 1.52±0.57 mg/L and 1.775±0.50 mg/L, respectively, which indicate compliance with the national standard of 10 mg/L (RS 564: 2023). The higher concentrations nitrate ions at the mining site and the treatment dams suggest a need for closer monitoring and improvements in the treatment methods at the dams.

4.2.2.3.Aluminium ions concentration

The results obtained for aluminium ions concentration at the four sampling sites considered in this study are presented in Table 3-8 below:

Table 3-6: Variation of aluminium ions concentration across sampling sites

Parameter	Sampling site	Mean and standard deviation	National Standard requirement	
Aluminium ions in mg/L	Site 1	25.34±41	2 mg/L, max.	RS EAS 1172: 2024
	Site 2	45.52±18.76		
	Site 3	7.82±14.92	5mgL, max.	RS 564: 2023
	Site 4	16.08±31.23		

The provided data in Table 3-8 on aluminum ion concentrations across different sampling sites and periods show significant variations, when compared to national standards. At the mining site, the aluminum levels changed from 3.74 mg/L in July 2023 to a substantial increase of 108.75 mg/L in January 2025, significantly exceeding the maximum limit of 2 mg/L specified in RS EAS 1172: 2024.At the treatment dams, the aluminum ions concentration ranged from

28 mg/L in November 2023 to 65.09 mg/L in January 2025, exceeding the permissible limits for drinking water treatment. At upstream river sites, the values remained within a relatively lower range, yet still above the 5 mg/L threshold outlined by RS 564: 2023. However, downstream, there was a dramatic spike, especially in July 2024 (71.94 mg/L), suggesting significant contamination post-mining, potentially due to runoff or effluent discharge from the mining operations. From the changes in aluminium ions concentration, wolfram mining's practices seem to contribute significantly to elevated aluminum levels, likely due to inefficient wastewater treatment systems. This comparison underscores the pressing need for enhanced monitoring, adherence to national standards and stronger regulatory enforcement to protect both human health and the ecosystem.

3.3 Variation of heavy metals across sampling sites

3.3.1 Arsenic

The results obtained for arsenic ions concentration at the four sampling sites considered in this study are presented in Table 3-9 below:

Table 3-7: Variation of Arsenic ions concentration across sampling sites

Parameter	Sampling site	Mean and standard deviation	National Standard requirement	
Arsenic in mg/L	Site 1	0.130±0.11	0.01 mg/L, max	RS EAS 1172: 2024
	Site 2	1.14±1.50		
	Site 3	0.0032±0.004	0.05 mg/L, max	RS 564: 2023
	Site 4	0.004±0.004		

The data presented in table 3-9 indicate that arsenic levels at the mining site show a progressive increase from 0.037 mg/L in July 2023 to 0.24 mg/L in January 2025, with a mean concentration of 0.130 ± 0.11 mg/L, which exceeds maximum tolerable limit of 0.01 mg/L specified in the national standard, RS EAS 1172: 2024). In the same way, arsenic concentrations in treatment dams shows variations, reaching a peak of 3.28 mg/L in November 2023 and declined to 1.05 mg/L in January 2025 resulting in a mean value of 1.14 ± 1.50 mg/L. These values indicate inefficient treatment processes in mitigating arsenic contamination. Compliance to the standard requirement is observed for samples collected at upstream and downstream points on Nyabarongo river.

3.3.1.1.1 Cadmium ions

The results obtained for cadmium ions concentration at the four sampling sites considered in this study are presented in Table 3-10 below:

Table 3-8: Variation of cadmium ions concentration across sampling sites

Parameter	**Sampling site**	**Mean and standard deviation**	**National Standard requirement**	
Cadmium in mg/L	Site 1	0.0065±0.0037	0.01, max	RS EAS 1172: 2024
	Site 2	0.037±0.014		
	Site 3	0.00325±0.0045	0.005, max	RS 564: 2023
	Site 4	0.004±0.005		

The results indicate in table 3-10 that the wastewater released from the mining site was compliant before its discharge in the dams as for all the data obtained are below the maximum tolerable limit of 0.01 mg/L, specified in RS EAS 1172:2024 which is the applicable national standard. Wastewater discharged from the treatment dams has higher concentration in cadmium ions and it is not compliant to the tolerable limit of cadmium specified in RS EAS 1172:2024. Compliance to the standard requirement is observed for samples collected upstream on Nyabarongo river. the highest value recorded in July 2024 for water discharged to the environment from the dams.

3.3.1.1.2 Chromium ions

The results obtained for chromium ions concentration at the four sampling sites considered in this study are presented in Table 3-11 below:

Table 3-9: Variation of chromium **ions concentration across sampling sites**

Parameter	**Sampling site**	**Mean and standard deviation**	**National Standard requirement**	
Chromium in mg/L	Site 1	0.008±0.010	1.0 mg/L, max	RS EAS 1172: 2024
	Site 2	0.031±0.017		
	Site 3	0.1115±0.25	0.05	RS 564: 2023
	Site 4	0.011±0.01		

The data provided in Table 3-11 indicate that for the mining site, the chromium levels are consistently low across sampling periods, with a mean concentration of 0.008±0.010 mg/L, which is below the maximum limit of 1.0 mg/L specified in the national standard, RS EAS 1172: 2024. At the treatment dams, the levels obtained, with a mean concentration of 0.031±0.017 mg/L, are compliant to the maximum limit set in the national standard. Similarly, the chromium concentrations remain within acceptable limits at downstream points on Nyabarongo river. The upstream site on Nyabarongo river shows a higher average concentration (0.1115±0.25 mg/L), which exceeds the RS 564: 2023 standard of 0.05 mg/L. The non-compliance to the national standard requirement was observed upstream on

Nyabarongo river in January 2025. For other sampling sites, chromium was not detected in January 2025.

3.3.1.1.3 Iron ions

The results obtained for iron ions concentration at the four sampling sites considered in this study are presented in Table 3-12 below:

Table 3-10: Variation of iron ions concentration across sampling sites

Parameter	**Sampling site**	**Mean and standard deviation**	**National Standard requirement**	
Iron as Fe in mg/L	Site 1	1.787±2.61	3.5 mg/L, max	RS EAS 1172: 2024
	Site 2	53.31 ±40.67		
	Site 3	12.53±22.07	Not covered	RS 564: 2023
	Site 4	19.60±32.72		

The data provided in Tale 3-12 indicate that, for wastewater collected at the mining site, iron concentration was compliant with the requirement of 3.5 mg/L specified in the standard (RS EAS 1172: 2024) except in July 2024 where non-compliance was observed with the recorded level of 6.38 mg/L. The treatment dams show higher concentrations indicating a high level of iron contamination post-treatment which may result from the previous accumulation of metals in the treatment dams. The iron concentrations upstream and downstream of the river remain elevated), with downstream sites showing a mean concentration of 19.60±32.72 mg/L. At these points, assessment of compliance is hampered since there are not acceptable limits specified in the current national standard, RS 564: 2023. It is important to consider that wolfram mining company needs to improve its waste management and water treatment processes to comply with national environmental standards. Additionally, the high variability of iron concentrations in treated water calls for a better monitoring of mining discharge systems to mitigate the adverse environmental impacts.

3.3.1.1.4 Lead ions

The results obtained for lead ions concentration at the four sampling sites considered in this study are presented in Table 3-13 below:

Table 3-11: Variation of Lead ions concentration across sampling sites

Parameter	Sampling site	Mean and standard deviation	National Standard requirement	
Lead as Pb in mg/L	Site 1	0.80±1.94	0.01 mg/L, max	RS EAS 1172: 2024
	Site 2	3.63±7.15		
	Site 3	0.008±0.0032	Not covered	RS 564: 2023
	Site 4	0.008±0.0023		

The data presented in Table 3-13 indicate that at the mining site, the lead concentration changed from 0.003 mg/L and 0.012 mg/L in 2023 and 2024.The highest value of 4.764 mg/L was recorded in January 2025, far exceeding the acceptable limit of 0.01 mg/L specified in RS EAS 1172: 2024, the applicable national standard. This indicates a significant contamination event or irregular mining activity at that point in time. Lead concentrations in the treatment dams showed a similar trend, with values ranging from 0.034 mg/L to 14.366 mg/L, indicating a potential accumulation or improper treatment of wastewater. Upstream and downstream of the river, concentrations were generally within the lower range. Since there is no requirement for lead concentration provided in the standard for ambient water, it becomes a challenge to assess compliance of lead ions concentration for water upstream and downstream on Nyabarongo river. Compared to the upstream and downstream river sites on Nyabarongo, which show relatively lower concentrations, it is noted that the contamination is primarily localized around the mining operations. Regular monitoring and effective treatment are needed to ensure protection of surrounding water bodies and biodiversity conservation.

3.3.1.1.5 Manganese ions

The results obtained for manganese ions concentration at the four sampling sites considered in this study are presented in Table 3-14 below:

Table 3-12: Variation of Manganese ions concentration across sampling sites

Parameter	Sampling site	Mean and standard deviation	National Standard requirement	
Manganese in mg/L	Site 1	3.57±1.81	1 mg/L, max	RS EAS 1172: 2024
	Site 2	9.53±6.97		
	Site 3	0.53±0.80	1 mg/L, max	RS 564: 2023
	Site 4	0.253±0.13		

The data given in Table 3-14 show that from the mining site, manganese levels vary between 2.02 mg/L in July 2023 and 7.10 mg/L in January 2025, with a mean concentration of 3.57

mg/L, exceeding the maximum tolerable limit of 1 mg/L specified in the applicable national standard, RS EAS 1172:2024. In comparison, the treatment dams show even higher concentrations, with the highest level of 19.47 mg/L recorded in March 2024. This indicates significant contamination from the mining process. The upstream site on Nyabarongo river, demonstrates lower manganese concentrations, with values varying between 0.11 mg/L and 2.14 mg/L, yet still greater than the maximum tolerable limit of 1 mg/L set in the Rwanda standard. Meanwhile, downstream levels remain within acceptable limits with variability and the highest concentration of 0.43 mg/L observed in July 2023. The findings from Wolfram Mining reflect a clear non-compliance to national standards in the mining and treatment dam sites, which might be attributed to inefficient waste management practices or lack of proper treatment processes. In light of this, urgent corrective measures are required to comply with national standards.

3.3.1.1.6 Copper ions

The results obtained for copper ions concentration at the four sampling sites considered in this study are presented in Table 3-15 below:

Table 3-13: Variation of copper ions concentration across sampling sites

Parameter	Sampling site	Mean and standard deviation	National Standard requirement	
Copper in mg/L	Site 1	1.60±1.61	1.0 mg/L, max	RS EAS 1172: 2024
	Site 2	10.55±6.46		
	Site 3	0.24±0.56	Not covered	RS 564: 2023
	Site 4	0.54±1.175		

The test results for copper ions concentration for wastewater collected from the mining site and the dams does not comply with the tolerable limit set in RS EAS 1172: 2024.

The results presented in table 3- 15 revealed that at the mining site, copper concentrations varied from 0.404 mg/L in July 2023 to 4.764 mg/L in January 2025, with a mean of 1.60 mg/L and a standard deviation of 1.61, exceeding the maximum tolerable limit of 1.0 mg/L set in Rwanda standard, RS EAS 1172: 2024). This suggesting potential contamination at the mining site, possibly due to mining activities. The treatment dams show even higher copper concentrations, ranging from 6.66 mg/L in November 2023 to 19.932 mg/L in March 2024, with a mean of 10.55 mg/L and a standard deviation of 6.46. This also illustrates poor treatment to remove copper from wastewater prior to its discharge in the environment. In contrast, upstream concentrations remained very low (<0.001 to 0.011 mg/L) except in January 2025 where it increases up to1.384 mg/L making the average to become 0.24 mg/L. At downstream point on Nyabarongo river, concentrations showed higher variability, peaking at 2.64 mg/L in July 2024. Since there is no requirement for copper concentration provided in the standard for ambient water, it becomes a challenge to assess compliance of copper ions concentration for water upstream and downstream on Nyabarongo river. The results of this study can be linked to improper mining waste management practices, insufficient wastewater treatment and possibly inadequate compliance monitoring.

3.4 Relationship between mining activities and Nyakabingo and Nyabarongo water quality.

3.4.1 pH

The pH levels measured at the mining site (3.2- 4.3) and treatment dams (2.6) indicated that the values obtained are out of the range 5 to 9 provided in the national standard RS EAS 1172. The sites above are in the closest surroundings of the pollution source.

During tungsten underground mining, acid formation primarily occurs due to the oxidation of sulfide minerals present in the ore body particularly pyrite (FeS_2) and other iron sulfides (Punia & Singh, 2021). This process is commonly referred to as acid mine drainage (AMD) or acid rock drainage (ARD) and follows these key reactions:

(a) Oxidation of pyrite (primary acid formation)

When sulfide minerals, especially pyrite, are exposed to oxygen and water during mining activities, they undergo oxidation, producing sulfuric acid (H_2SO_4) and iron ions:

$2FeS_2+7O_2+H_2O \rightarrow 2Fe^{2+}+4SO_4^{2-}+4H^+$

This reaction releases sulfate (SO_4^{2-}) and hydrogen ions (H^+), leading to acidification of water.

(b) Further oxidation of ferrous iron

The Fe^{2+} ions released in the first reaction can be further oxidized in the presence of oxygen and water, producing ferric iron (Fe^{3+}):

$4Fe^{2+}+O_2+4H^+ \rightarrow 4Fe^{3+}+2H_2O$

Ferric iron is more reactive and can further catalyze the oxidation of pyrite, accelerating acid formation.

(c) Hydrolysis of ferric iron

Ferric iron hydrolyzes in water, producing additional acidity:

$Fe^{3+}+3H_2O \rightarrow Fe(OH)_3(s)+3H^+$

The formation of ferric hydroxide ($Fe(OH)_3$), commonly seen as a yellow or orange precipitate in mine drainage areas, is an indicator of acid mine drainage.

The overall stoichiometric pyrite oxidation reaction can be written as:

$4FeS_2+15O_2+14H_2O \rightarrow 4Fe(OH)_3+8SO_4^{2-}+16H^++heat$

The formation of H^+ ions indicates an acidic pH.

The records upstream and downstream on Nyabarongo river is within the range set in the standard. At the upstream point, where there is slight direct impact from mining operations, the pH remained within a tolerable range. From the site observation, it was noted that there are streams whose water flow towards Nyakabingo stream at downstream. This dilution of water reduces the concentration of hydrogen ions making less impacts on the Nyabarongo river which is far from the Nyakabingo stream at approximately 40 km.

3.4.2 Electrical conductivity

The results of electrical conductivity obtained are within the range specified in the standards. However, higher electrical conductivity values were obtained at the mining site and wastewater discharged to the environment from treatment dams in comparison to the values obtained at upstream and downstream sites. That increase in electrical conductivity is due to the release of dissolved ions such as sulfates, heavy metals and other ionic contaminants. The exposure of minerals to oxygen and water lead to AMD, which in turn, dissolves metals into conductive ions (Simate & Ndlovu, 2014). Consequently, elevated EC values suggest higher concentrations of dissolved solids, which can negatively affect aquatic life and render water unsafe for use in agriculture (Adnan et al., 2024).

3.4.3 TSS and Turbidity

The results indicated that before wastewater from the mining site enters the treatment dams, TSS and turbidity values were high. As these dams play an important role in promoting sedimentation and filtration by a controlled environment where water flow slows down, allowing heavier particles such as sediments, metal oxides and other suspended materials to settle at the bottom through gravitational settling (Awotwi et al., 2022). Additionally, treatment dams incorporate engineered structures like retention ponds and vegetation, which enhance sediment capture and further reduce TSS levels. Over time, finer particles coagulate and settle, leading to improved water clarity and quality before the treated water is discharged into natural watercourses. This process significantly mitigates the adverse impacts of mining-related erosion and sediment transport, thereby protecting aquatic ecosystems and downstream water users (Affandi & Ishak, 2019).

3.4.4 TDS

There is a strong positive correlation indicating that more dissolved solids released from unmanaged tailings or accumulation of TDS in the treatment dams overtime. It was noted that the concentration of TDS at the mining site and treatment dams was higher than that at upstream and downstream on Nyabarongo river. TDS levels are influenced by various mining activities. Underground mining exposes sulfide-rich minerals to oxygen and water, leading to AMD which, in return, dissolves salts and heavy metals, increasing TDS concentrations (Punia & Singh, 2021). The scale of mining activities further increases this effect, as larger operations generate more waste, leading to higher leaching of dissolved ions into surrounding water bodies (Awotwi et al., 2022).The distance of mining operations from the river affects the extent of contamination, with closer sites allowing for quicker transport of dissolved solids via runoff and groundwater flow, while farther sites may experience natural attenuation (Karaca et al., 2018).The release of tailings or effluents into the treatment dams contributes to TDS accumulation, as these waste materials contain soluble salts and heavy metals that dissolve over time.

3.4.5 Sulphate ions concentration

The results obtained indicated that the concentration of sulphate ions is higher at the mining site and treatment dams. In sulfide-rich ore deposits, mining operations facilitate the exposure of pyrite (FeS_2) to oxygen and water, resulting in the formation of sulfuric acid, which dissolves into sulfate ions and increases their concentration in nearby water bodies (Sarmiento et al., 2022). In Nyakabingo mine, the production of tungsten increases annually. Large-scale mining operations often involve extensive excavation, ore processing and waste disposal, leading to increased exposure of sulfide minerals to atmospheric and hydrological conditions (Punia & Singh, 2021). As a result, higher volumes of acid mine drainage (AMD) and sulfate-rich leachates can enter the river system. As mining activities occur in close proximity to the river, sulfate-rich leachates, tailings seepage and contaminated runoff quickly reach the Nyakabingo stream, leading to significant changes in its sulfate concentration. Conversely, the level of sulphate decreases due to natural attenuation processes such as dilution and ion adsorption by soil and sediments before it reaches the Nyabarongo River.

3.4.6 Heavy metals

The test results have indicated that the concentration of heavy metals such as Al, Mn, Fe, As, Cd, Cu, and Pb is not compliant and the significant increase in concentration was observed for wastewater at the mining site and treatment dams. This influence is due to the mining activities. Underground mining exposes metal-bearing ores to water and oxygen, resulting into the oxidation and dissolution of these metals, which then leach into surface water systems (Simate & Ndlovu, 2014). Additionally, as large-scale operations generate more waste rock, tailings and acid mine drainage (AMD), increasing metal mobilization (Awotwi et al., 2022). The distance of mining operations from the river affects metal transport, with closer sites allowing for direct runoff into the river, while distant sites experience metal attenuation through soil adsorption or precipitation and this is the case for Nyabarongo river located far from the pollution source (Karaca et al., 2022).

4. Conclusion and recommendations

The findings of this study confirm that mining activities significantly affect the physicochemical properties of water in Nyakabingo stream and Nyabarongo river, particularly near the mining site and treatment dams. pH levels were found to be highly acidic, falling below national standards, due to acid mine drainage and the oxidation of sulfide minerals. Elevated concentrations of sulfates and heavy metals such as Al, Mn, Fe, As, Cd, Cu, and Pb were recorded near mining zones, accompanied by increased electrical conductivity and TDS. Although decantation in treatment dams reduced TSS, the overall inefficiency of the current treatment methods points to the need for improved wastewater management systems. The dilution effect of tributary streams and distance from the mining site helped reduce pollution levels in Nyabarongo River downstream, yet persistent risks remain.

To address these challenges, it is recommended that the Government of Rwanda emphasize enforcement of environmental standards, update national water quality standards to include all critical parameters and improve coordination between regulators, communities and mining operators. Mining companies should adopt advanced treatment technologies such as chemical precipitation and constructed wetlands, ensure proper use of neutralizing agents and establish protective buffer zones. Communities are encouraged to explore alternative water sources to reduce dependency on potentially polluted surface water. Future research should explore the reuse of mining tailings as industrial raw materials to promote sustainable resource use and reduce environmental harm.

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