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Surface and Groundwater Quality and Flow Dynamics around a Tropical Highland Open Pit Mine, Amid Progressive Ecological Rehabilitation

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Abstract

It is essential to investigate the impact of tropical highland open pit gold mines on surface and groundwater quality and flow dynamics. Samples from the Twangiza gold mine, with long term mining activities, including small-scale mining were analyzed in an accredited South African Laboratory. Results indicate that TDS and EC were higher in the mine site due the concentration of many metals. DO values were higher downstream. ORP and pH levels were similar at all site positions. **Upstream**: Fe, Si, K, Mg, Al have the highest concentrations (14.0 - 23.1 mg·l^{-1}). P, Pb, B, Ti, Sr, Ag, Ni, Ba, and As have concentrations ranging from 0.1 - 0.9 mg·l^{-1}. Li and Au have the lowest concentrations (0.01 - 0.05 mg·l^{-1}). Zn was also relatively abundant upstream, most likely airborne by the plant generator smoke. **Within the mine site**: Si, Al, Mg, Fe are found in higher concentrations (19 - 50 mg·l^{-1}). These are followed by K, As, and P (1.4 - 4 mg·l^{-1}). Ni, Ti, Ag, Sr, Ba are also found in lesser concentrations (0.2 - 0.7 mg·l^{-1}). The groundwater flow remained consistent. This study has the advantage of having continuously followed up a large number of heavy metals during years.

Keywords

Mining, Water Quality and Quantity, Heavy Metals

1. Introduction

Mining activities, including mine closure and all its facets that are of importance to the mining sector and the society at large, are subject to government regulations, aiming at maximizing the positive outcome for economic and social development and minimizing the negative impact on the environment. This delicate balance is far from simple and it requires scientific input (Mucina et al., 2019). Also, water is linked to nearly every type of mining industry, whether as groundwater, surface water, coastal water, or process/wastewater and, accordingly, there is a substantial need to assess water quality and quantity conditions in all phases of mining: exploration, operation/production and decommissioning (DHI SOLUTION, n.d.).

One primary source of mining air pollution comes from mineral extraction, including the processes of excavation, blasting, transportation of materials, and wind erosion. Vehicles and heavy equipment used during mining also produce exhaust emissions that contribute to these pollution levels. With metal mining, very high temperatures are used as part of the smelting process. Though technology has improved significantly over the past 50 years, smelting can still contribute to a variety of toxins, including: lead, nitrogen and sulfur, mercury, sulfur dioxide, zinc, cadmium, and uranium sulfur dioxide can lead to acid rain, which can wreak havoc on environmental health. Smelting also releases large amounts of greenhouse gases into the atmosphere, which has severe and long-lasting impacts (DHI SOLUTION, n.d.).

Heavy metal (HMs) contamination in soils is known to be harmful to the environment. Though the existence of contaminants in the soil may be caused by natural processes, it is believed to be mostly due to human activities (Murtaza et al., 2014; Nurcholis et al., 2017; Ebenebe et al., 2017; Aruna et al., 2024; Shapi et al., 2021). The discovery of extensive gold deposits has raised concerns about potential heavy metal contamination in waterways and adjacent soils, particularly in developing nations like Nigeria where environmental regulations may not be stringent enough Adekiya et al. (2024). Natural processes that lead to the emergence of contamination in the soil include volcanic activity and andesitic minerals alteration. As caused by human activities these processes may include mining, industry, households and agriculture mainly (Nurcholis et al., 2017). Gold mining activities consisting of material mining and processing to separate the gold from the tailings, both of which can potentially lead to the emergence of heavy metal contamination in the soil (Nurcholis et al., 2017), are very similar to the situation expected at the Twangiza mine.

It shall be noted that metabolic and physiological processes of plants, humans and even microorganisms are positively influenced by HMs such as Cu, Ni, Co, Cr, Fe, I, Mn, Mo, Se and Zn, commonly known as micronutrients or essential elements (Ebenebe et al., 2017). In contrast, HMs such as Ag, As, Cd, Hg and Pb are not biologically important to living organisms and are usually very toxic to human health and biota in the environment (Ebenebe et al., 2017), hence the need for scrutiny of the situation in peculiar situations.

The issues of HMs contamination of local, regional, and global environment emanate directly from natural sources and indirectly from anthropogenic activities such as mining, rapid industrialization, urbanization, improper waste management and other local and regional man-made activities (Hadzi, 2022).

It is well known that water resource availability (i.e., water quantity) can be impacted by mining in numerous ways. Mines need water for many reasons, such as grinding ores to separate minerals, washing or transporting materials, drilling, controlling dust, cooling machinery, pit flooding, properly executing mine closure, and supporting the needs of workers (IISD, 2022).

Alluvial gold prospecting in the Twangiza area, with a surface area of 1156 sq·Km started in 1938 in the Kadubo, Kashwa, Mufwa and Mwana Rivers. Between 1982 and 1984, another company undertook a feasibility study and recommended a mine and a mill capacity of 600 t/day on a 300 days per year schedule. More advanced work was conducted between 1997 and 1998 with over 9000 of meters drilled along 800 m strike length; mapping and re-sampling of all accessible adits and undertook close to 11,000 m of air-borne geophysics (Twangiza Gold Mine, 2007). The current mine infrastructure was constructed from 2009. This operating open pit gold mine is located on a hilly topography averaging between 2000 and 2500 m asl with the highest hill reaching 3250 m. This exceptional situation makes it unique in a way that its hydrology and direction of surface and groundwater may impact the surrounding communities if not well considered. The ridge that the mine occupies is surrounded by the Mwana river to the West and the Lulimbohwe river to the East (each with lowest flow of 0.25 $m^3 \cdot s^{-1}$); both alpine rivers which fast flow to form the Kadubo river that reaches the Ulindi river, a tributary of the Congo River.

This paper projects to analyze results obtained from environmental monitoring since 2012, including the water flow rates of both surface and groundwater to identify the impacts on water quality and quantity. The dynamics of water flow rates and quality of surface and groundwater will be investigated. In the meantime, the topographic characteristics of study sites, as well as the depth of the water table, will be measured to develop a conceptual model of the potentiometric flow of water.

2. Material and Methods

2.1. Study Area

The Twangiza open pit gold mine is located in the Mwenga district, South Kivu Province, DR Congo, 45 km crow flight south-southwest of Bukavu, a city at the shore of Lake Kivu. The hilly topography averages between 2000 - 2500 m asl; the highest close-by hill reaching 3250 m. The lowest temperature is 13˚C while its maximum 23˚C on average. The study area is shown in **Figure 1**.

One of the two main rivers, the Mwana has been severely affected by sediment-laden runoff from small scale mining activities to the extent that its valley bottom has been transformed into a swathe of disturbed sediment that runs over 3 - 4 four kilometers downstream of the mine main deposit. The Lulimbohwe river, which is also fast flowing and has a steep slope, has been impacted by small scale mining at a lesser extent than the Mwana river (Twangiza Gold Mine, 2013).

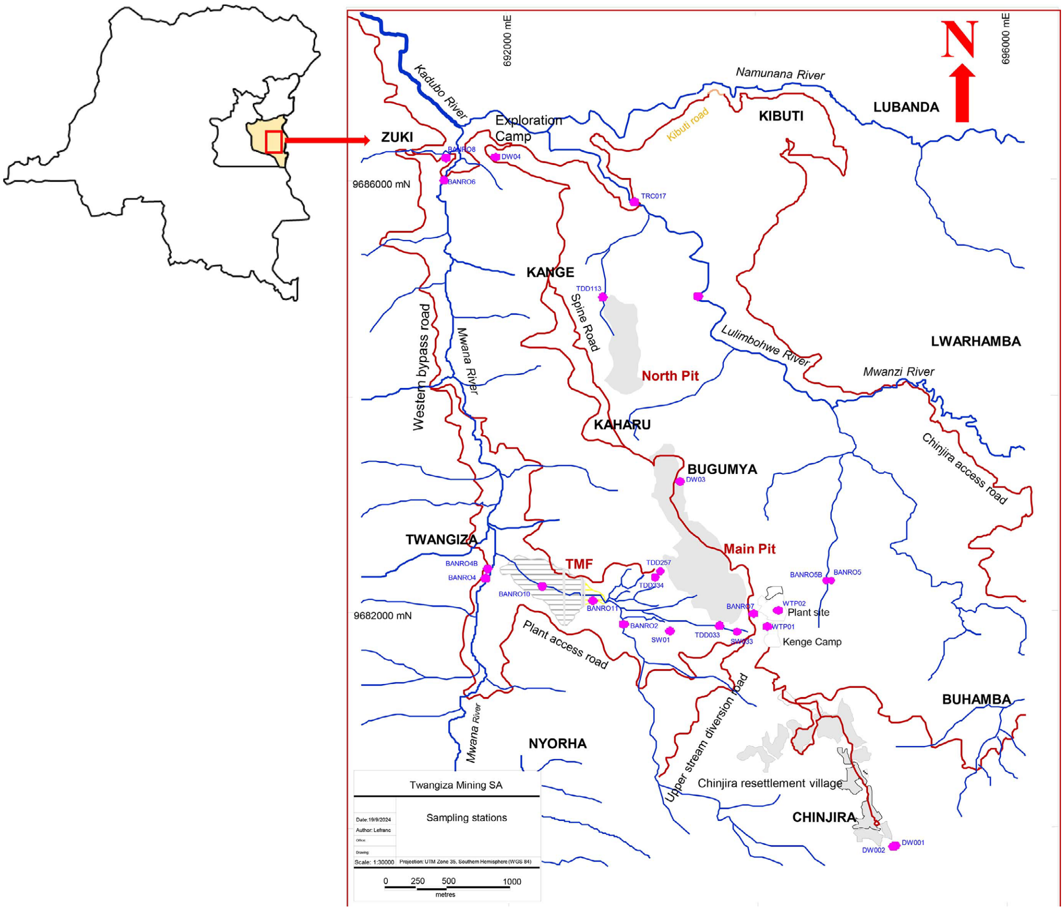

Figure 1. Map of the study area showing the water quality sampling sites.

2.2. Surface and Groundwater Monitoring

2.2.1. Water Sampling

The surface water monitoring stations were selected within the Twangiza mine open pit orebody, downstream of the orebody and within the surrounding rivers (Mwana and Lulimbohwe Rivers). Control stations were selected on zones that do not interfere and/or relate with the orebody from its sides and upstream.

Monitoring plan maps were generated using the Twangiza gold mine digital terrain model (DTM) and their associated topographic contours. The softwares Surpac 6.6.2 (×64) and MapInfo Professional 8.5 helped finalize the plan maps, with aid of georeferenced Lidar images that were collected using a helicopter, during the airborne geophysics (aeromagnetic and radiometric) and the Lidar topographic survey conducted in 2007 and 2008. Surface water samples were collected directly from the stations using labelled sampling bottles that included a 1000 ml plastic bottle (un-acidified) and a 250 ml plastic bottle (acidified). The samples were sent monthly to Waterlab (Pty) Ltd in Pretoria, South Africa for analysis of heavy metals as well as rare earths and a few non-metals. This encompassed 66 elements analysed by the Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) scan. In situ physicochemical parameters were measured using a pH-meter (TPS WP-81), a Thermo Orion Star A322 for pH, temperature, Dissolved Oxygen (DO), Oxydo-Reduction Potential (ORP), electrical conductivity (EC) and total dissolved solids (TDS) and a BLE-C600 Bluetooth Water Quality Tester for pH, EC, TDS, ORP and Temperature. When the samples were very turbid, a 20 L plastic bag was used to collect the samples, allow the suspended matters to settle and then collect the supernatant liquid for analysis.

A Solinst Water Level Meter 101[1] was used to measure the level of the water table. An FP series Portable Digital Water Velocity Meter was used to measure the flow velocity ($m \cdot s^{-1}$)[2]. Two more parameters were measured, being the stream width (m) and the stream depth (m). The product of the three provided the discharge in ($m^3 \cdot s^{-1}$), which was later converted to liters per second ($L \cdot s^{-1}$). When the use of the Velocity Meter was not possible, a graduated bucket and a stop watch were used to estimate the flow, also expressed in $L \cdot s^{-1}$. In this case, all the flow from an artesian borehole, or a pipe was collected in the bucket using a stopwatch at a set volume.

2.2.2. Sampling Procedures of Freshwater Benthic Macroinvertebrate as Bioindicators

Freshwater benthic macroinvertebrates were collected to serve as bioindicators, for the indication of the overall water quality in the rivers, downstream of the mine which receive the run off from its catchment area. The benthic macroinvertebrates were sampled, over a 3-day period in September 2024, using a 30-cm wide D-frame aquatic net (Ngera et al., 2019; Shabani et al., 2019; Baguma et al., 2024) with a mesh size of 300 µm (Touzin, 2008). At each site, the net was cast in a downstream to upstream direction, for a distance between 0 and 20 m (Baguma et al., 2024). Three replicate samples were collected and all substrates were explored by hand to detect any clinging specimens (Khettar et al., 2013; Reyjol et al., 2013; Ngera et al., 2019; Baguma et al., 2024). The specimens were grouped according to the sites and dates of sampling and placed in appropriate jars labelled plastic containers, fixed with 95% ethanol (Shabani et al., 2019) and then transported to the laboratory for further analysis. In the Biology Laboratory of the Université Officielle de Bukavu, the collections were placed on a 50 µm mesh sieve for pre-sorting (AFNOR, 2010) using small tweezers (Baguma et al., 2024). The specimens were identified using collection guides (De Moor et al., 2003a; De Moor et al., 2003b; Day et al., 2003; Stals & De Moor, 2007; Tachet et al., 2010).

2.2.3. Data Analysis

The descriptive statistics of the water quality parameters were computed on Jamovi 2.3.28 software. The decision trees were computed on SPSS 23.0 software (machine learning module) to describe the distribution factors for each of the

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[1] https://www.solinst.com/products/level-measurement-devices/101-water-level-meter/.

[2] https://www.awmeasurements.com/open-channel-flow-meters/p/digital-water-velocity-meter.

water quality parameters, the means and standard deviations and the n were given at each node.

The principal components analysis and the discriminant were run on Past 4.11. The PCA allowed to identify the trends of the various significant parameters at each associated component so that the sampling stations were grouped in terms of low-high values in their water quality. The discriminant analysis had the same purpose of grouping the sample locations (upstream, within site and downstream) based on their multivariate heavy metal, on the one hand, and physico-chemical parameters, on the other hand. Also, the cluster analysis allowed to draw the dendrogram classification and the corresponding Morisita Index similarities between the sampling stations.

The path diagram (PCA in Jasp 0.18.3.0) allowed to detect the assemblages of heavy metals. Such assemblages were useful to find the % of variances explained in each component, parameters one by one and the weight of each component loading in the system (eigenvalues). Benthic macroinvertebrates were collected to serve as bio-indicators, for the indication of the overall water quality in the rivers, downstream of the mine, which receive the run off from its catchment area.

2.2.4. Modeling of Water Flow Directions

The ground topography was depicted from Lidar topographic images as well as the DTM model, GPS and Trimble data. From these, the UTM coordinates for the whole study area, allowing to have the Easting, Northing and Elevation data. The elevation data helped to produce topographic contours using the Surpac software. The elevation and contours data coupled with the measured water table levels assisted in schematizing the ground water flow directions. These also assisted in developing the hydrological conceptual model. The schematic model was developed on the prevailing topography over the open pit mine site and the infrastructure locations as well as the various drill holes so the information on the location and water table levels was availed.

3. Results and Discussion

3.1. Characteristics of the Surface and Groundwater

3.1.1. Physico-Chemistry

pH

The average water pH is 6.9 ± 1.56 (n = 3 924 samples) in the study area, lying within the acceptable limits as far as the DRC, and IFC effluent discharge guidelines are concerned (6 - 9). pH varied by Year, Season and by station. Only the station, Banro 10, originating from a spring located upstream of the mine, and above the tailings dam was acidic (5.66). The other stations had a pH ranging from 6.4 - 8.0. Banro 11, the tailings dam, had an alkaline pH (9.5) since it received plant slurry, whose pH is purposely controlled between 10.5 - 11 to ensure better cyanide management in the process plant and avoid generation of HCN, the toxic form of cyanide (ICMI, 2009). All the other study stations showed stable pH values with the coefficient of variation ranging from 4.7% - 16.8%. pH did not vary significantly by source whether upstream, within the mine site or downstream. pH was significantly higher in boreholes and rivers. It was moderate on tap and water treatment plants. The lowest pH values occurred mainly in spring water, which are mainly not in contact with the mine site activities. pH is the single most important variable influencing the behavior of metals in the environment (Ebenebe et al., 2017). Metal complexes with sulfates, fluorides, chlorides and phosphates, are most stable and important below pH 7, with metal complexes that have carbonates and hydroxides becoming increasingly more important above pH 6 - 8 (Ebenebe et al., 2017).

TDS (mg·l^{-1})

The average TDS value was 142 ± 193 mg·l^{-1} (n = 3 053; CV = 135.9%), fully within drinking water acceptable limits (WHO, 2008; Bisleri, 2024), and strongly fluctuated between stations and years. The lowest values (22.6 - 31.9 mg·l^{-1}; n = 291 - 373) occurred in drinking water (taps and springs). The highest TDS values occurred at Banro 11, the tailings dam ($\bar{x}$ = 941 ± 297.7 mg·l^{-1}; n = 99), which is explained by the mineral composition and chemical elements present in the plant slurry that is discharged in there. TDS values in lakes and streams are typically found to be in the range of 50 to 250 mg·l^{-1} (Vernier, 2005). In areas of especially hard water or high salinity, TDS values may be as high as 500 mg·l^{-1} (Vernier, 2005). Water can be classified by the level of TDS: Fresh water: TDS is less than 1000 ppm; Brackish water: TDS = 1000 to 10,000 ppm; Saline water: TDS = 10,000 to 35,000 ppm; Hypersaline: TDS greater than 35,000 ppm. Generally drinking water has a TDS below 500 ppm. Higher TDS Fresh Water is drinkable but taste may be objectionable (Water Science School, 2018).

Electric conductivity (EC, µS·cm^{-1})

Unlike pH which varied mainly along the years, the EC changed mostly between sampling stations. The average EC was 216 µS·cm^{-1} with strong variations between stations as shown by its standard deviation of 299.58 and a coefficient of variation (CV) as high as 139%.

The highest EC values (1 360 µS·cm^{-1}) were found at the Tailings pond, alike TDS, followed by a station on the Mwana river (Banro 3), with intensive small scale mining (577 µS·cm^{-1}). The lowest EC values were found in drinking waters, springs and upstream surface waters, showing that that EC was heavily influenced by industrial and small scale mining activities. In this category with lower EC, we found clean control stations with low human activities, where few households are settled. Within site, the average EC was 652.7 ± 129.65 µS·cm^{-1} (n = 78) as opposed to downstream, which was higher (737.6 ± 323.3 µS·cm^{-1}; n = 78) but more unstable.

Dissolved Oxygen, DO (mg·l^{-1})

Dissolved oxygen values strongly fluctuated ($\bar{x}$ = 4.9 ± 15.34 mg·l^{-1}; n = 1394 samples; CV = 319%) with inter-annual variations. In most cases the DO values were higher in the rainy season. DO values were higher downstream. DO values strongly fluctuated within the mine site, but they were similar to those upstream.

DO was highest in both rivers and taps. Moderate values were observed in springs comparatively closely followed by boreholes and treatment plants. Healthy natural waters are known to generally have dissolved oxygen concentrations above 6.5 - 15 mg·l^{-1} (Wetzel, 2001).

However, in the study area, no fish was found probably due to the reason that artisanal mining activity is intense, leading to regular and intermittent Dissolved Oxygen depletion in the rivers under study. As very low values of DO imply that the water becomes anoxic, all the stations were checked and found that all of them had closer to no oxygen in them at a point in time. Control stations were also checked for minimum and maximum DO levels (mg·l^{-1}). Banro 1 had 0.14 - 17.34 mg·l^{-1}, Banro 7 had 0.08 - 9.34 and Banro 9 0 - 9.17. This indicates when DO levels dropped to 0 no aerobic organism survived in these waters as they would suffocate, which later returned back to normal values for healthy waters. This general situation may be attributed to anthropogenic activities such as agriculture, poor protection of river banks and at times alluvial activities that disturbs the sediments and cause eutrophication. Also, it was found that DO levels varied with Years (higher values recorded in 2010 and lower ones in 2011), followed by Seasons with lower values during the dry season. This does not show a clear attributable impact of the Twangiza mine establishment in the region.

Fish were only recorded from the upstream sites of the Mwana, Mwanzi and Lulimbohwe, and all appear to be one species, *Amphilius kivuensis* (GroundTruth (2009). *A. kivuensis* does not fall into any conservation categories according to the Iternational Union for Conservation of Nature (IUCN, 2024).

Temperature (˚C)

Temperature values were quite consistent ($\bar{x}$ = 19˚C ± 7.11˚C; n = 1670). They varied mainly between years with higher values occurring in 2012, 2013 and 2014 ($\bar{x}$ = 19.7˚C ± 8.58˚C; n = 1052) and lower values in 2010 and 2011 ($\bar{x}$ = 18.3˚C ± 3.22˚C; n = 618). Water temperature was quite stable as expected in tropical waters at all stations (CV = 5% - 20%). The lowest variability (CV = 5% - 8%) was observed in groundwater stations.

On the higher side, temperature was higher in the rainy season with stronger variations ($\bar{x}$ = 20.0˚C ± 9.61˚C; n = 815) than in the dry season ($\bar{x}$ = 18.5˚C ± 2.75˚C; n = 237) and at higher elevations (beyond 2300 m asl). Temperature was consistent at all of the stations though it was significantly higher downstream followed by stations within the mine site and upstream. This is typical of the tropical region, which is supposed to be warmer, except in higher elevations where temperature drops. Hence higher temperature in the lower elevation reaches (1500 - 1900 m asl), gradually decreasing in the mine site (2100 - 2250 m) and in upper reaches (2250 - 2600 m asl). Temperature was quite similar between the water source types.

Temperature is known to have a significant effect on the conductivity and TDS of water. As the temperature of water increases, the conductivity and TDS also increase (Dewangana et al., 2023).

Oxidation Reduction Potential, ORP (mV)

ORP values were on average 114.5 ± 83.78 mV; n = 1680 samples. The lowest values (32 - 48 mV; n = 138 - 169) occurred in some boreholes and upstream surface waters. The highest ORP values were observed in some taped drinking water and springs ($\overline{x}$ = 240.9). The reasons for ORP variation are unclear. ORP values were minimal in boreholes, and returned similar values in rivers, springs, taps and treatment plants.

The following assemblages were identified for physico-chemistry parameters: DO and ORP; pH and temperature; and TDS and EC. These are shown in Figure 2.

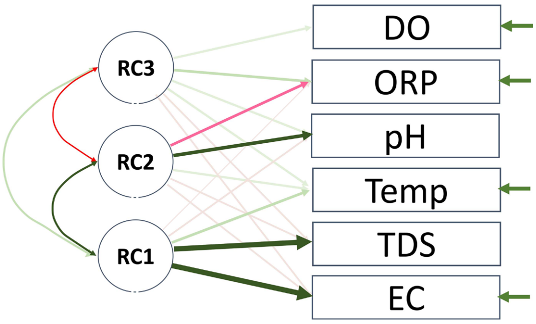

Figure 2. Physico-chemical parameter assemblages in water samples (path diagram).

The 3 components accounts for 43% of the physico-chemistry information, given that many other parameters were not measured. B priority, Factor 1 alone explained 35% of the variance. EC and TDS variances were utterly explained by component 1. Factor 1 correlated positively with Factor 2 (γ = 0.42), as shown in Table 1. EC and TDS variances were explained 100% in Factor 1 and pH in Factor 2 (27%).

Table 1. Factors explaining the variance of the physico-chemical parameters' assemblages.

	Factor 1	Factor 2	Factor 3
Factor 1	1	0.416	0.142
Factor 2	0.416	1	−0.083
Factor 3	0.142	−0.083	1

Figure 3 displays a classification dendrogram and its corresponding Morisita Index similarities between the sampling stations as far as water quality is concerned.

It can be seen that the cluster TDD033, TDD113, TDD334 makes sense as these stations are all linked to the general groundwater and water table, that has similar characteristics, and is not affected by materials from the mine orebody.

Groundwater flowing north westerly, it would be expected that its quality is similar, which is depicted by the fact that TRC017 and TDD327 are quite similar though located respectively downstream and within the mine site, as shown in Figure 4.

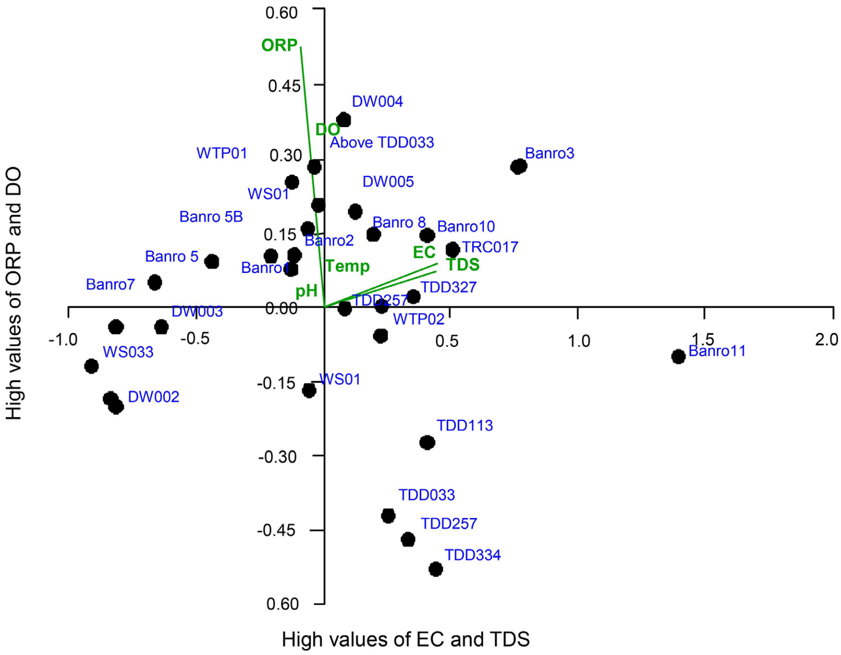

Figure 3. Dendrogram of the water quality parameters (classical clustering, Morisita similarity index).

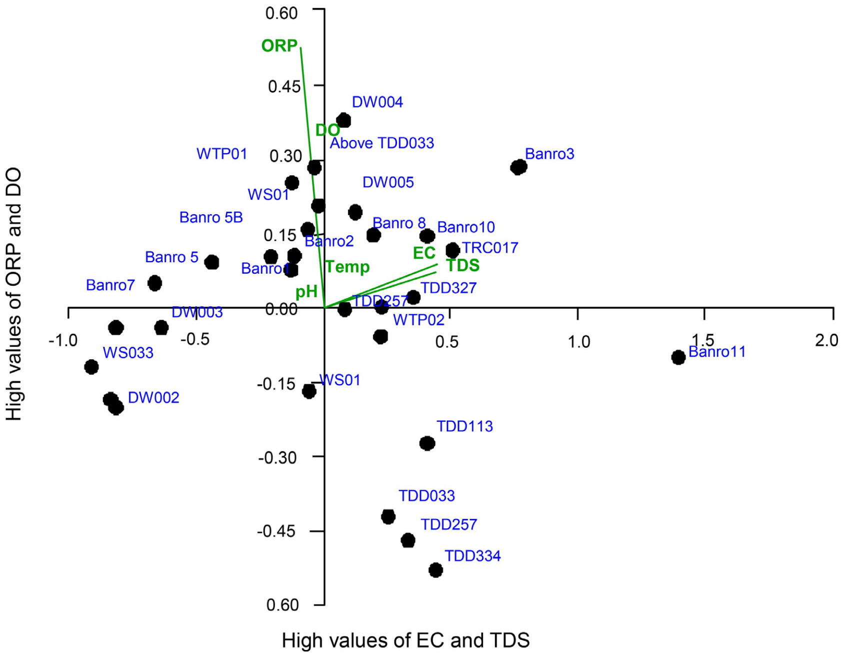

Figure 4. Principal Component Analysis (PCA) of the water quality parameters at the study stations from 2010-2016.

The stations Banro11, Banro3, Banro6, Banro10, TRC017, TDD334, TDD327 had higher values for EC and TDS as opposed to DW003, DW002, DW001, Banro4B, Banro7, Banro5 which had lower ones. WTP01 and WTP02 had lower ORP and DO values as compared to DW003 and Banro7 which had higher values. This is shown in Table 2 and Figure 5.

Table 2. Sampling stations' grouping using PCA.

Station water characteristics	Low values in station	High values in station
EC and TDS	W003, DW002, DW001, Banro4B, Banro7, Banro5	Banro11, Banro3, Banro6, Banro10, TRC017, TDD334, TDD327
ORP and DO		DW0004, WS033, DW005, Banro10, WPT01, WS01
ORP and DO	WTP01, WTP02	DW003, Banr07

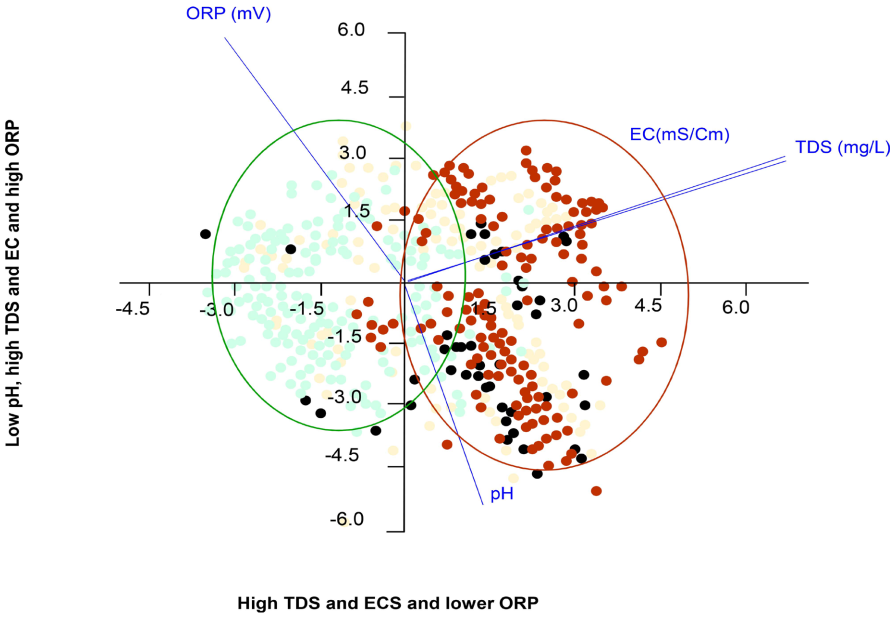

Figure 5. Discriminant analysis of physico-chemical parameters by sampling point position.

Brown color represents stations within mining site, green = upstream, yellow = downstream.

The pH was lower upstream than within site. This trend of pH was confirmed elsewhere in soil analyses (Basima et al., in press) in Twangiza area which has steep slopes. The EC and TDS are lower upstream than within site as shown by Kruskal-Wallis test, too (respectively, $p = 0.002$ and $p = 0.005$), likely because metal concentrations are higher within site. The ORP is significantly lower within the core area than upstream ($p = 0.02$) and lower than downstream ($p = 0.03$). In this area where the elevation is very high upstream (2350 - 2400 m vs 2100 - 2300 m asl within the mine site), temperature is lower upstream than within the mine core area ($p = 0.03$) and lower than downstream ($p = 0.02$).

3.1.2. Heavy Metals (HMs) and Rare Earths Dynamics

The occurrence of HMs concentration by location around the mine orebody is presented in Table 3 and in Table 4 by water source type.

Table 3. Occurrence of heavy metals and some non-metals and rare earths and physico-chemical parameters within the mine site as compared to upstream and downstream.

	Upstream	Downstream	Within the mine site
Heavy metals and	Pb, Zn	Ag, Al, B, Ba, Fe, Ga, Ge, Ho, Rb, Tb, Ni, Ti, Y.	Ag, Au, As, Bi, Si, Cd, Ce, Sm, Co, Cr, Ni, Ti, Y, Dy, Er, Eu, Mo, Gd, Se, Cu, Mn, Pb, La, Fe, Cs, Ge, Ho, Rb, W, Tb
Non-metals and rare earths		K , Mg, Li	K, Na, S, P, Ca, Be, B, Li, Mg, S, Ca

Table 4. Dominant characteristics per water source type.

Borehole	Spring	River	Treatment plant	Tap	Pond
Ag, As, Ba		Al, B, Ba			Ca, Co, Ni
Be, Bi, Cd, Cr, Sn, Fe, Ga, Mg, Mn, P, Rb, Sr, S, Si	Be, Bi, Cd, Cr, Sn, K, Ga, Rb, Sr	Be, Bi, Cd, Cr, Sn, Ce, Fe, Ga, K, Mn, Rb, Sr	Be, Bi, Cd, Cr, Sn, Rb, S, Zn	Be, Bi, Cd, Cr, Sn, Rb	Na, Ti

Effects of seasons, location (upstream, downstream or within mine site) and water source type

The highest Nickel (Ni) concentration occurred within the mine site (0.096 ± 0.153; n = 381); 5 times more, then upstream 3.4 times more than downstream where the concentrations reach an increment of 47% as compared to upstream though. The concentration in the pond reaches 0.19 ± 0.195; n = 163 within the site.

From 2013-2017 the Ni concentrations reached 0.27 ± 0.196; n = 105 vs 0.05 ± 0.060; n = 58 from 2010-2012 i.e. a 5-fold increment.

The concentration of Titane (Ti) averaged 0.03 ± 0.056; n = 2059. The highest concentrations occurred in rivers and in the pond within the mine site and downstream (0.04 ± 0.077; n = 1029), two times more than in springs and boreholes, especially in 2016-2017 when the concentration reached 0.09 ± 0.146; n = 120 thus reaching 3.4 times more than in 2010-2013 earlier period. On average, the Ni values amounted to 0.04 ± 0.075; n = 2060.

Potassium (K) concentrations amounted to 1.5 ± 1.044; n = 2050 on average. The highest values were found in springs (2.3 ± 1.63; n = 189), reaching 4.1 ± 0.75 downstream, 2.4 times more than in the pond, boreholes, taps and treatment plants; and up to 4.1 ± 0.75; n = 80 downstream, i.e. 4 times more than in springs located upstream and 1.5 more than in rivers downstream as shown in Figure 6.

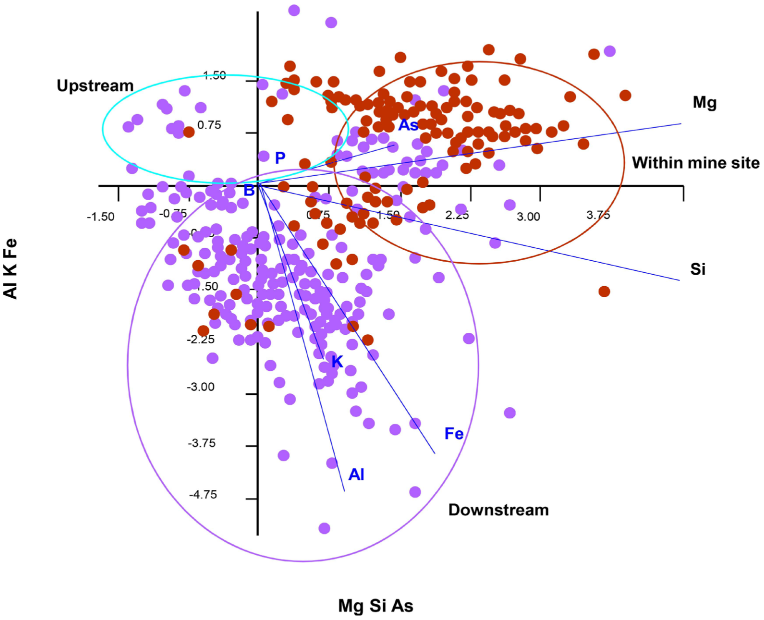

Figure 6. Discriminant analysis of HMs and rare earths by sampling point position. Blue = upstream; Brown = within mine site; violet = downstream.

The discriminant analyses quite clearly distinguish 3 zones. There are less Mg, Si, As upstream and more of them within the mine site. Several stations downstream have much Mg, Si, As, though quite a good number of them have less. But, there is more Al, K, Fe upstream alike stations within the mine site, as opposed to downstream. This is illustrated in Figure 7.

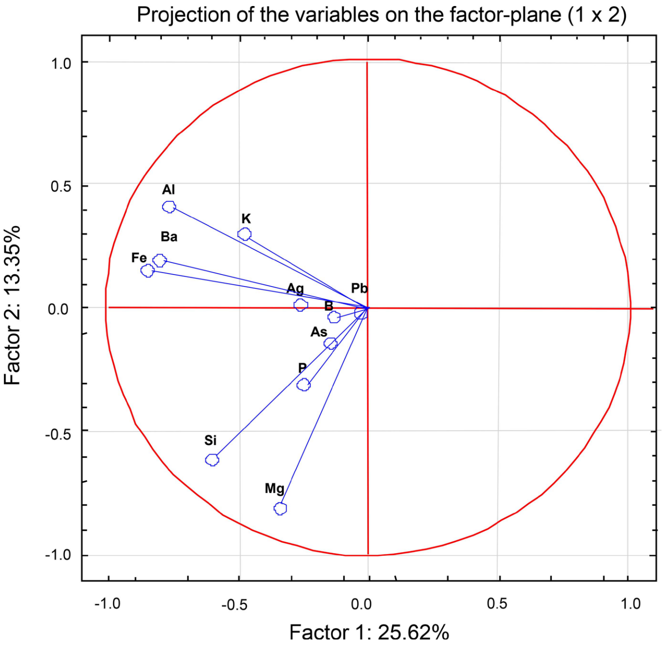

Figure 7. Co-occurrence of elements.

There is a high rate of co-occurrence between Si and Mg; Fe and Ba and Al.

The borehole waters had comparatively more Mg, Si, Fe and As. The distinct springs alike rivers had less K. More Al was observed on taps and treatment stations. But, most of the springs presented an intermediate situation as compared to boreholes and taps, as shown in Figure 8.

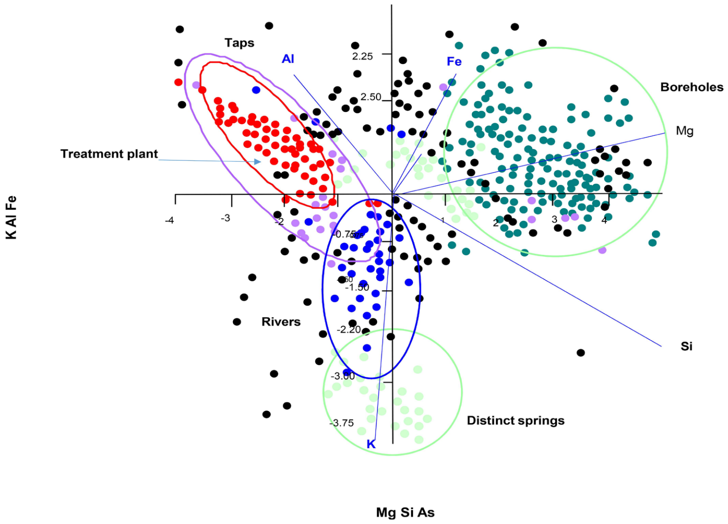

Figure 8. Discriminant analysis of HMs composition by water source type.

A schematic representation of the dynamics of chemical elements at the Twangiza mine site and small scale mining is shown in Figure 9.

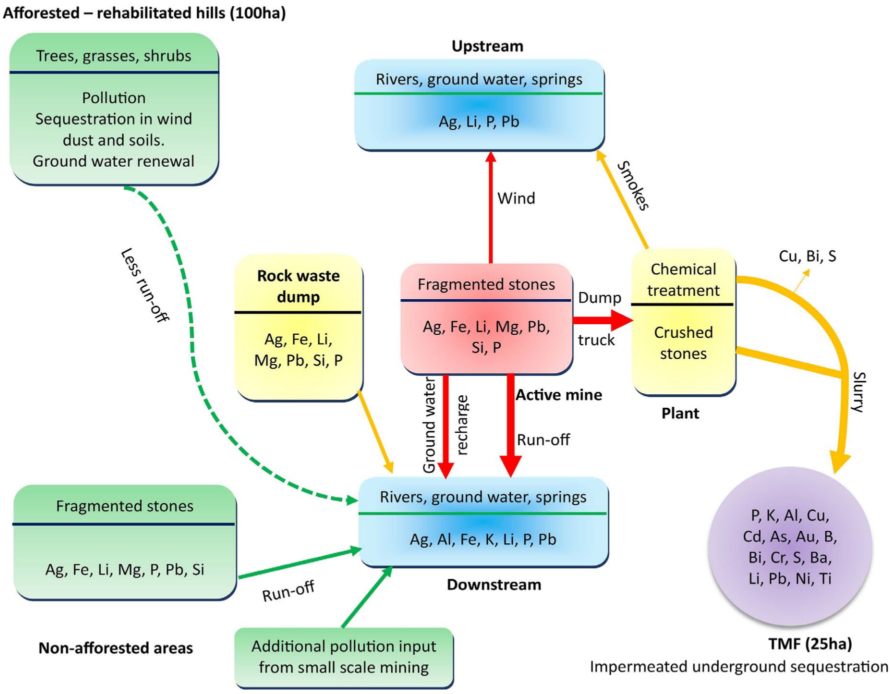

Figure 9. Schematic representation of chemical elements' dynamics at the Twangiza mine site and small scale mining in the surroundings.

Downstream, the prevailing elements are Si, Al, Fe, Mg (max 26.2 - 59.4 mg·l^{-1}); followed by K, As, P, Ti, Ba, Ag (max 1.2 - 6.5 mg·l^{-1}); B, Ni, Sr are found downstream too, with lower levels (max 0.3 - 0.6 mg·l^{-1}); Sr, Au Li, Pb are found in much lower concentrations downstream (0.05 - 0.09 mg·l^{-1}).

Within the mine site, Si, Al, Mg, Fe are found in higher concentrations (19 - 50 mg·l^{-1}). These are followed by K, As, and P (1.4 - 4 mg·l^{-1}). Ni, Ti, Ag, Sr, Ba are also found in lesser concentrations (0.2 - 0.7 mg·l^{-1}). The lowest concentrations involve Li, Pb, Au (0.01 - 0.06 mg·l^{-1}).

Upstream, Fe, Si, K, Mg, Al have the highest concentrations (14.0 - 23.1 mg·l^{-1}). P, Pb, B, Ti, Sr, Ag, Ni, Ba, and As have concentrations ranging from 0.1 - 0.9 mg·l^{-1}. Li and Au have the lowest concentrations (0.01 - 0.05 mg·l^{-1}).

Fe is found everywhere and has been detected during the baseline study with elevated values almost throughout the river system (Morgan et al., 2009).

The tailings management facility (TMF) contains more As, Fe, Al, Mg, Si, K, Ni, P at its surface (1.4 - 22.0 mg·l^{-1}). B, Ti, Sr, Ba and Au have maximal concentrations ranging between 0.2 - 0.5 mg·l^{-1}; while Ag, Pb and Li have maximum concentrations ranging between 0.02 - 0.04 mg·l^{-1}.

Al was significantly more concentrated downstream as compared to stations within the mine site. This is probably due to the fact that Al is one of the main components of clay (Kodama & Grim, 2024), which originates from the watershed runoff and small-scale activities who wash river sediments as part of their activities.

As was highly significantly concentrated within the mine site. Its concentration was much lower downstream and no trace was found upstream. Arsenic occurs naturally in soil and rock and can dissolve into groundwater (MDH, 2010). It is introduced into water through the dissolution of rocks, minerals and ores from industrial effluents, including mining wastes, and via atmospheric deposition (WHO, 2003; WHO, 2008). Actually, arsenic is the 20th most common element in the earth's crust, and is associated with igneous and sedimentary rocks, particularly sulfidic ores (Reis & Duarte, 2019). There are several natural sources, as well as anthropogenic actions that may introduce arsenic into groundwater and drinking water. The problem of Arsenic in gold mining is crucial because the element is abundant, mobile in acidic reactions, and this element is very dangerous for human life (Nurcholis et al., 2017). Elevated Arsenic was found in the upper reaches of the Mwana River, Upstream, at the alluvial area on the Mwana River (both downstream) and during the baseline study in 2008 (Morgan et al., 2009), before the mine exploitation started.

Cesium (Cs) fluctuated very much within sites, reaching sometimes 0.20 mg·l^{-1}. It was very low upstream and downstream. Cs is a naturally-occurring element found in rocks, soil, and dust at low concentrations. Granites contain an average Cs concentration of about 1 part of Cs in a million parts of granite (ppm) and sedimentary rocks contain about 4 ppm. Natural Cs is present in the environment in only one stable form, as the isotope ^{133}Cs (ATSDR, 2004).

Cu and Mn were significantly highly concentrated within the mine site as compared to downstream and were quite absent upstream. Elevated Mn was already detected at the baseline study in the Mwana and Lulimbohwe Rivers, downstream of the mine (Morgan et al., 2009). Dy, Er and Eu were highly significantly more concentrated within the mine site as compared to downstream and upstream, whose values were quite similar.

Fe was similarly concentrated downstream (with high variability) as compared to the mine site. Its concentrations were much lower but present upstream. Ga was significantly more concentrated downstream as compared to within the mine site, and lower but present upstream.

Gd, P, Se and Yb (Ytterbium) were highly significantly concentrated within the mine site as compared to downstream and upstream, the latter being similar. Ge, He, Li, Rb (Rubidium), Th and W were significantly more concentrated within the mine site followed quite closely by downstream and upstream, the latter being similar.

Zr and K were higher downstream, average within the mine site and lower upstream, but present.

La was highly significantly more concentrated within the mine site and much lower downstream and upstream.

Mg, Ni, Ti, Y (Yttrium) were highly significantly more concentrated within the mine site followed by downstream and lesser, but present upstream. Elevated Ni was found in the Mwana and Lulimbohwe rivers during the baseline study (Morgan et al., 2009). Nd (Neodyme) and Pr (Praseodymium) were highly significant present within the mine site and quite absent downstream and upstream.

Pb was similarly concentrated within site and upstream where it fluctuated and it was significantly lower, though not by far, downstream. However, the baseline study informs that elevated Pb was found in the upper reaches of the Mwana River (Upstream) and both upstream and downstream of the Lulimbohwe River (Morgan et al., 2009). S was highly significantly concentrated within the mine site followed by far by the downstream water, but very unstable. This presence is due to the pyrite that is present in the lithology which is crossed by groundwater, hence is boreholes and the main mining site. Concentrations were much lower upstream but present for similar reasons.

Values of Sr were low everywhere though more concentrated within the mine site. Zn was more highly concentrated upstream followed by downstream and within the mine site, the latter being similar, hence Zn was evenly distributed.

Metals associated with gold mines, including Cd, Cu, Pb, and Zn may be dispersed downstream due to the weathering process of tailings. Thus, the extent and degree of heavy metal contamination around mines may vary depending on geochemical characteristics (Goldschmidt, 1937) and mineralization of tailings. Waste rocks are known to contain arsenic (As), mercury (Hg), cadmium (Cd), lead (Pb), and other toxic metals, which are extensively dispersed into the environment (Hadzi, 2022).

Predominant wind might have pushed Pb upstream (Pb being airborne) from the process plant, which may justify its presence. Factor 3 included Ti, Ni, Na, Cu, Co, Ca, Au and As. Se, Nd, Mn, La, Eu, Er, Dy, Ce and Al (to a lesser extent) were involved in factor 2. In Factor 1 (principal component), the elements were the following: Te, Sn, Rh, Rb, Pb, Mo, Li, Ge, Cr, Cd, Bi, Be and Ag. Part of Ni variance was also explained in Factor 2, alike Co, Er and Eu partly in factor 1. Components 1 and 2 were slightly correlated between themselves and with component 3 (r = 0.20).

Component 1 explained 36% of the variances and component 2 did it for 22%; while component 3 explained 14% of the variance; i.e. 72% altogether.

Assemblages of heavy metals and rare earths in water are presented in a form of path diagram in Figure 10.

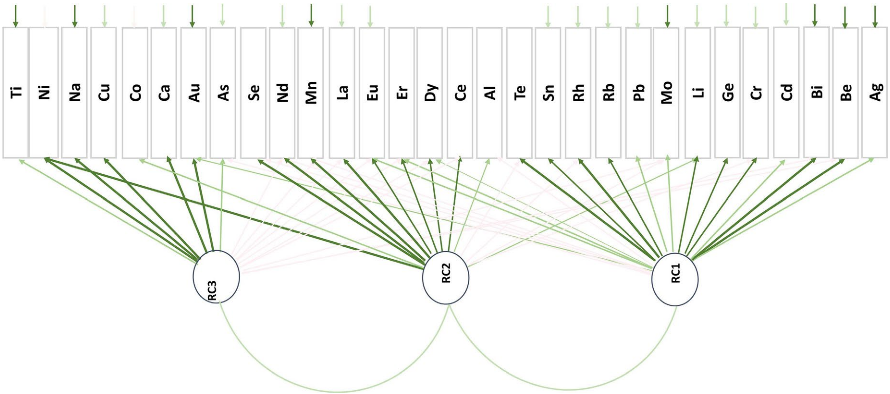

Figure 10. Heavy metals and rare earths assemblages in water samples (path diagram).

The first assemblage encompassing mainly the chalcophile's group of elements, i.e. Te, Sn, Pb, Ge, Cd, Bi and Ag is expected as they all have strong affinity to sulphur. They represent 54.0% in this principal component. In the same component, we found mixtures with a few lithophiles (30.8%), because we are dealing anyway with crushed or fragmented stones in the gold mine and lesser siderophiles (15.4%). In the same vein, lithophiles which form silicates justify the assemblage of La, Eu, Dy, Er, Ce and Al. The lithophiles represent 66.7% in the group PC or RC2, more so we found a high proportion of rare earths (83%), mainly lanthanids, among this lithophile group. These are: Nd, La, Eu, Er, Dy and Ce. The chalcophiles, the siderophiles and the biophiles just respectively represented 11.1% each in this assemblage. The third principal component is more heterogeneous regarding the geochemical classification within. The chalcophiles and the siderophiles are tantamount (37.5% each), while the chalcophiles and the lithophiles just respectively represent 12.5% each.

Thematic maps were found by chemical elements in the study area. Figure 11 illustrates this for Al and As, among many others.

3.2. Groundwater Elevation and Flow Directions

Results indicate that groundwater flow in the Twangiza study area is NW towards

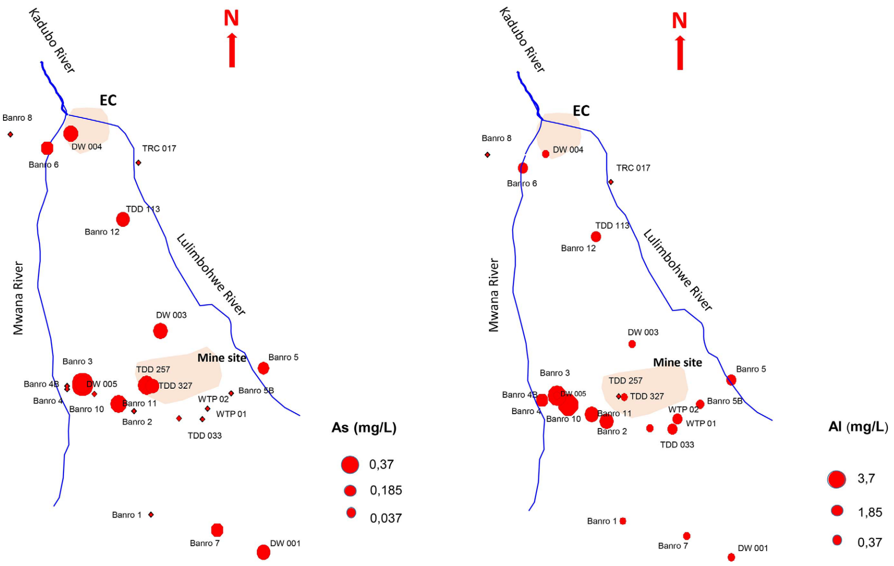

Figure 11. Thematic maps by chemical element found in the study area (Al and As among many others).

the Congo River sub-tributaries, following the topography. Significant water flow towards the Mwana River on the eastern side and the Lulimbohwe River on the western side of the summit ridge is expected along the faults, resulting in accumulation of groundwater in the alluvial deposits in the Mwana and Lulimbohwe Rivers' valleys. The faults in the lithology are believed to facilitate surface water infiltration from the ridge towards the limbs.

With the development and maintenance of the restoration stations, more surface water is believed to be captured by these ecosystems, allowing more water retention and gradual release for both surface and groundwater. This, in turn, facilitates the growth of native species, which, unfortunately continue to be threatened and cleared by the general community; the general community has still not understood the role of native species to the up keeping of the ecosystem, the landscape and their related services.

The depth of the water table ranges from around 90 m on the summit of the ridge to about a meter to the Mwana River valley (alluvium). A few artesian (free outflow of water) boreholes, intersecting the fractured aquifer, are found on the limbs of the Twangiza anticline.

A preliminary interpretation of the potentiometric surface based on the limited information and on the assumption that the groundwater daylights where the topography intercepts the rivers is given in Figure 12.

However, the derived potentiometric surface, as highlighted in Figure 12, gives a fair description of the region NW trending flow direction with locally deviating flow components due to the topography, feeding the Kadubo River.

Figure 12 actually shows altitudinal levels of 2700 m asl at the southernmost, by the Cinjira village, moving north towards the Twangiza gold mine process plant and pit at 2400 - 2300 m asl, 2000 to 1900 towards the limbs and 1700 m asl at the origin of the Kadubo River, where the Mwana and Lulimbohwe Rivers join.

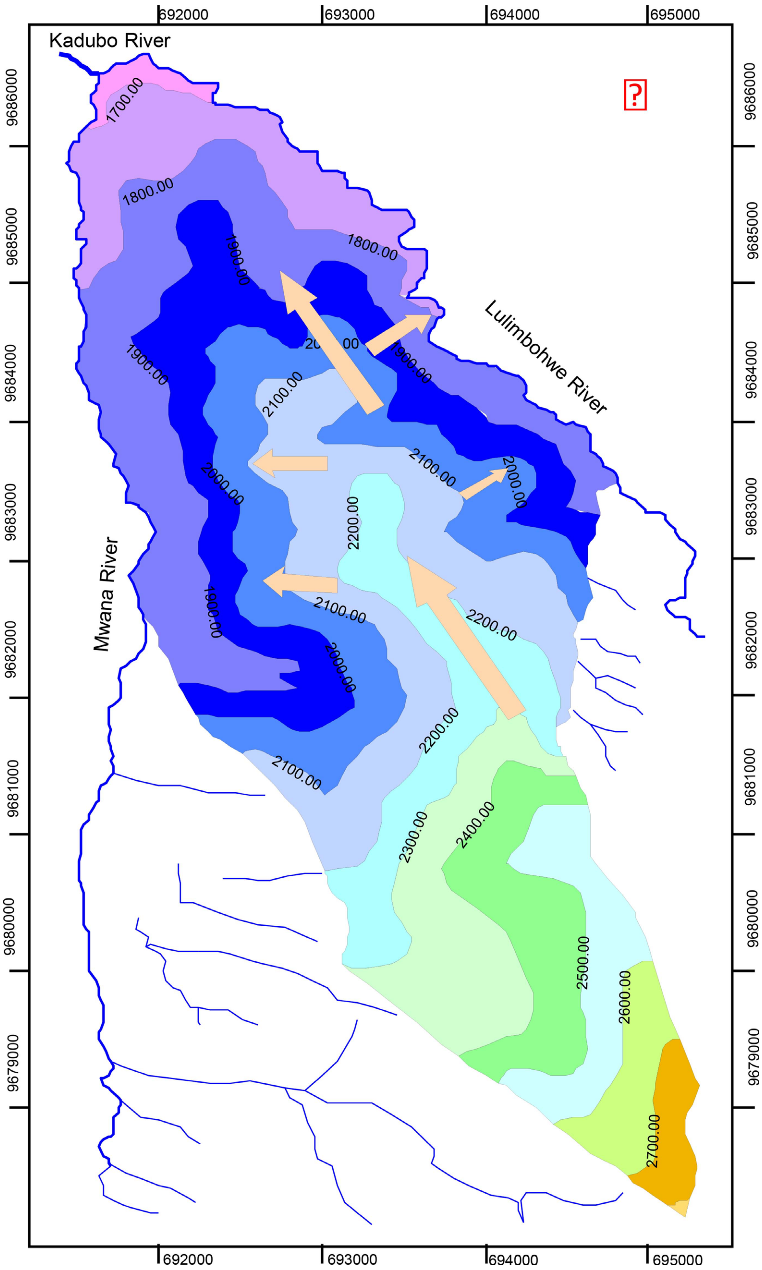

Figure 12. Preliminary interpretation of potentiometric surface and indicated groundwater flow directions.

Drilling/bore holes that intersected groundwater during the hydrogeological studies reported by end of year 2011, indicated that the level the water table was intercepted and the water flow in litres per second in the study area.

The level of the water table was lower when measured as compared to that at the time of drilling, when the water was hit. This lowering of the water table is probably due the fact that when a hole is drilled, pore pressure pushes the water through (capillary effect), hence showing as if the water table was higher. With time and the pressure fading away, the water table takes back its normal level. For example, in the Twangiza Main pit, TRC002 showed water at 66 m from the original topography at the time of drilling, while the dip meter showed the water table at 143 m depth.

It is also generally seen that the higher the elevation of the borehole, the lower the flow rate, except for 2 drill holes in the TMF area with respectively 0.23 and 0.53 $L \cdot s^{-1}$ (for TRC031 and TRC033).

Like the rest of the water cycle, groundwater is never completely still and in one place. Different aquifers and limiting layers of subterranean rocks (which water has a hard time entering) impact the direction and velocity of the groundwater's movement, what is referred to as groundwater flow (Ghaur & Friedl, 2023).

The faults that were depicted in the lithology are believed to facilitate surface water infiltration from the ridge towards the limbs, considering that hydraulic conductivity that was evaluated is part the two hydraulic parameters that should be taken into consideration as preliminary evaluation to the occurrence of groundwater reservoirs along with porosity (hatari Labs, 2017).

For direct impacts, natural replenishment of ground water occurs from both diffuse rain-fed recharge, which seems to be the case in the present situation, and focused recharge via leakage from surface water (that is, ephemeral streams, wetlands or lakes) and is highly dependent on prevailing climate as well as on land cover and underlying geology (hatari Labs, 2017).

3.3. Aquifer Parameters of the Geological Units and Related Conceptual Model

The hydraulic conductivity that assesses the infiltration rate in the various geological units, and shown in **Figure 13**, brought up the following results:

- a hydraulic conductivity of 0.01 - 0.1 $m \cdot day^{-1}$ for the weathered and fractured carbonaceous mudstone and feldspar porphyry in the hinge zone (Twangiza main pit). At depth, where the mudstone is less weathered, the hydraulic conductivity decreases to 0.0001 - 0.001 $m \cdot day^{-1}$.
- A higher hydraulic conductivity of 0.1 - 5 $m \cdot day^{-1}$ for the core of the anticline in the Twangiza Main pit (TDD265).
- TDD 257 intercepted a fault breccia with open fractures, which might correspond to one of the major NNE striking faults. This borehole continues to be artesian, thirteen years later.
- the hydraulic conductivity of the weathered carbonaceous mudstones and feldspar porphyry on the western limb of the anticline (Twangiza North pit) is higher than 1 $m \cdot day^{-1}$, decreasing with depth as less weathered rocks are intercepted. The higher conductivities appear to be controlled by the weathered and altered zones rather than being structurally controlled.

The Lulimbohwe River continues to be recharged while the TMF plays a surface water retention role, that was originally flowing towards the Mwana River. However, much of the surface water flowing to the Mwana River has been diverted around the TMF, mainly through the Upper and Lower Stream diversions to ultimately reach back the Mwana River. The Mwana River also continues to be

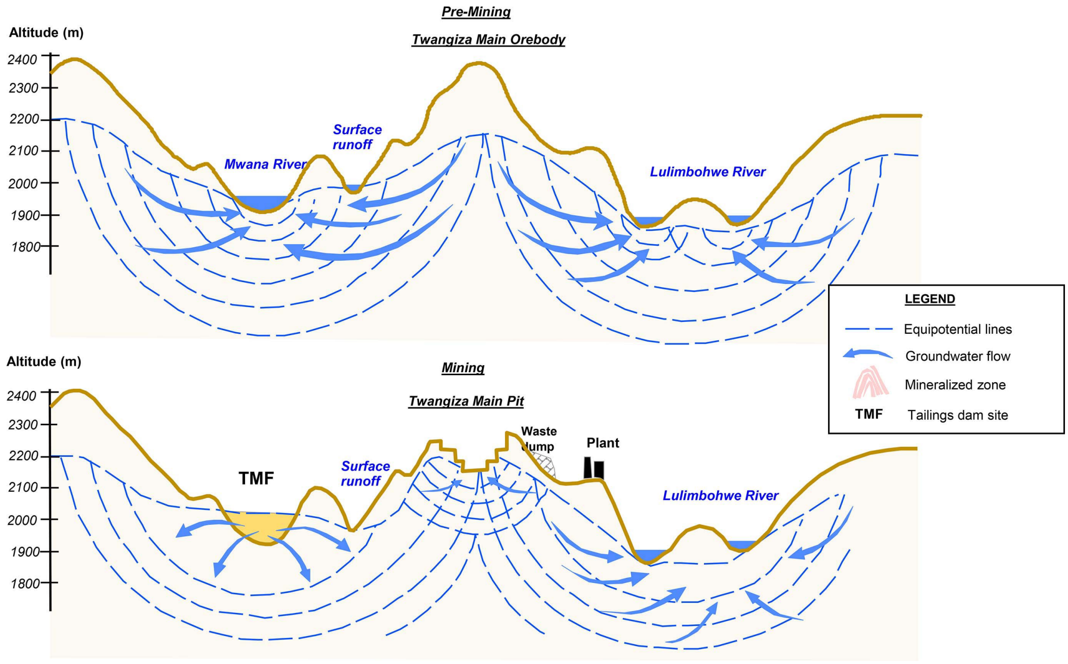

Figure 13. Cross-sectional conceptual model of the Twangiza mine orebody before exploitation as well as that with mining activities and infrastructure.

fed with groundwater passing beneath the TMF pond, such as with the water passing through the V-notch, named Banro 10 and located in the TMF valley. Precipitation and surface runoff recharges the aquifers through the geological layers and fractures.

3.4. Benthic Macroinvertebrates Bioindication of Overall Water Quality in the Rivers Downstream the Mine

Bioindicators were considered in the present paper as a final confirmation method and are illustrated in Table 5.

Table 5. Values of biological metrics and indices at sampling sites from the rivers around the Twangiza mine.

	Kadubo River (2 rivers confluence)	Lulimbohwe Bridge	Raw Water	Mwana River near TMF	Mwana River Bridge
Composition community and diversity					
No.Tot.Tax	14	16	23	14	8
No.Tot.Ind	87	83	477	153	51
% EPT	12.64	45.78	51.99	22.22	9.80
% Dipt	37.93	16.87	9.43	19.61	52.94
% Chiro	0.00	0.00	0.42	0.00	1.96
% Ins	100.00	96.39	97.48	96.08	98.04
% Ins-Dipt.Tax	62.07	79.52	88.05	76.47	45.10
% No Ins.Tax	0.00	3.61	2.52	3.92	1.96

Continued

H	2.10	2.14	2.38	1.98	1.44
D	0.18	0.15	0.14	0.17	0.33
eH/S	0.58	0.53	0.47	0.52	0.53
J	0.80	0.77	0.76	0.75	0.69
Biotic index					
FBI	4.64	5.23	3.86	4.34	3.86
Water Quality	Good	Fair	Very good	Good	Very good
Pollution Level	Unpolluted	Lightly polluted	Very unpolluted	Unpolluted	very unpolluted

The Raw water site originates from upper hills of the Lulimbohwe river with minimal or no interference from industrial and small scale mining activities; hence its very good quality and very unpolluted status. As the river continues its course, small scale mining activities become intense, increasing the water turbidity, diverting the course of the river, utilizing Hg for Au amalgamation, destroying river banks, opening trenches and adits in the nearby hills, using gasoline water pumps. This explains why the river water quality is categorised as fair and lightly polluted. Also, the flow rate is high (11 $L\cdot s^{-1}$) which boosts its self-purification capacity. Lulimbohwe is an alpine river with low temperature (average 8˚C), increasing its dissolved oxygen levels. The river also receives the surface water runoff from the mines main waste dump (500 - 1000 m distance). The Mwana river is categorised as good to very good on its course indicating that it is lightly impacted on some sections by small-scale mining activities, up to the confluence with the Lulimbohwe, forming the Kadubo river, which is also categorised as good. Kadubo, a first order river in the local system which receives waters from the Mwana and the Lulimbohwe (2nd order); thus its higher flow rate boosts its self-purification capacity, especially because it receives other inlets which are affected neither by the industrial nor the small scale mining activities.

The macroinvertebrates genera *Potamon*, *Neoperla*, *Libellula*, *Simulium*, *Odontomyia*, *Leptonema*, *Hydropsyche*, *Hydrophila*, *Leptecho*, *Oligoneuriops*, *Baetis*, *Acentrella*, *Leptonema*, *Leptecho* and *Potamon* genera indicated better natural water quality. Only *Acoenagrion*, *Acellus* and *Dineteus* were more abundant in the river stations polluted by small scale gold mining, as opposed to the less polluted river stations. But, among the genera observed, *Acoenagrion* is the best statistically significant candidate bioindicator of heavy pollution by small-scale gold mining.

Observations on bioindicators corroborate the information obtained from heavy metals and physico-chemistry, which indicate that the values are within the acceptable levels.

4. Conclusion

A decade-long environmental monitoring, with samples shipped to an accredited lab in South Africa brought up results that show non-significant changes in natural waters, within the accepted standards, regarding quality and quantity. This includes rivers, boreholes and springs; upstream, within mine site and downstream, as opposed to the tailings management facility which collects the polluted slurry by pipe from the treatment plant, while cyanide is controlled in the detoxification tanks, prior to discharge. This encouraging information should not be taken for granted but used with care and with the continuation of mine exploitation, contamination may occur; especially if the guidelines provided in the environmental and social management plans are not followed and the environmental department given the required consideration. The tailings management facility may break down, causing spillage. In this case the contaminated content will mix with natural waters. Also, the lithology of the mine encompasses sulfidic material that releases sulfuric acid when in contact with oxygen and water. Acid mine drainage is a high risk observed in several open pit mines (not only gold) over the world.

The concentrations of various heavy metals around the mine site and downstream is linked with the run-off from excavated and fragmented stones within the mine pits. The results indicate that TDS, EC were higher in the mine site.

Upstream, Fe, Si, K, Mg, Al have the highest concentrations (14.0 - 23.1 $mg \cdot l^{-1}$). P, Pb, B, Ti, Sr, Ag, Ni, Ba, and As have concentrations ranging from 0.1 - 0.9 $mg \cdot l^{-1}$. Li and Au have the lowest concentrations (0.01 - 0.05 $mg \cdot l^{-1}$). Zn was also relatively abundant upstream most likely airborne by the plant generator smoke. **Within the mine site**, Si, Al, Mg, Fe are found in higher concentrations (19 - 50 $mg \cdot l^{-1}$). These are followed by K, As, and P (1.4 - 4 $mg \cdot l^{-1}$). Ni, Ti, Ag, Sr, Ba are also found in lesser concentrations (0.2 - 0.7 $mg \cdot l^{-1}$). The lowest concentrations involve Li, Pb, Au (0.01 - 0.06 $mg \cdot l^{-1}$). The following elements occur both in the mine and in the tailings management facility: Bi, Cd, Ce, Sm, Co, Cr, Y, Dy, Er, Eu, Mo, Gd, Se, Cu, Mn, La, Cs, Ge, Ho, Li, Rb, W, Tb, Na, Mg, Ca, Na, S, Ca, Be, B. Specifically, **the tailings management facility (TMF)** contains more As, Fe, Al, Mg, Si, K, Ni, P at its surface (1.4 - 22.0 $mg \cdot l^{-1}$). B, Ti, Sr, Ba and Au have maximal concentrations ranging between 0.2 - 0.5 $mg \cdot l^{-1}$; while Ag, Pb and Li have maximum concentrations ranging between 0.02 - 0.04 $mg \cdot l^{-1}$. **Downstream**, the prevailing elements are Si, Al, Fe, Mg (max 26.2 - 59.4 $mg \cdot l^{-1}$); followed by K, As, P, Ti, Ba, Ag (max 1.2 - 6.5 $mg \cdot l^{-1}$); B, Ni, Sr are found downstream too, with lower levels (max 0.3 - 0.6 $mg \cdot l^{-1}$); Sr, Au Li, Pb are found in much lower concentrations downstream (0.05 - 0.09 $mg \cdot l^{-1}$). B, Ga, Ge, Ho, Rb, Tb, Ni, Y, and Li had similar concentrations downstream alike within the mine site. In the aftermath of the mine closure, a closure plan may consist of levelling the surface and for new land use of the 25-hectares tailings facility for crops, fodder, and afforestation.

The groundwater flow kept the same NW direction towards the Congo River sub-tributaries, following the topography and its flow remained consistent, indicating that the nearby Itombwe montane forest reserve is stabilizing the zone, in addition to the positive impact of the progressive rehabilitation project as well as its related community-based induced afforestation program that facilitate the surface water retention, gradual and regular infiltration reaching the water table at a regular basis.

This study has the advantage of having continuously followed up a large number of heavy metals during years, yielding results which shed light to new legislation on open pit rehabilitation and alluvial small scale gold mining, relevant in many countries.

Regarding the flow direction and rate, the groundwater continues to have a north western flow, following the topography and springs continue to be found upstream, by the side of the mine and downstream. Currently, even the boreholes within the mine site continue to daylight with 5.5 $L \cdot s^{-1}$. Way below the tailings management facility, groundwater continues to daylight at the V-notch area with 11.2 $L \cdot s^{-1}$ in November 2024. At many other places, untapped springs are visible around the mine site, upstream and downstream, highlighting that the groundwater flow is healthy and live.

The nearby Itombwe montane forest reserve is stabilizing the zone, in addition to the positive impact of the progressive rehabilitation project as well as its related community-based induced afforestation program that facilitate the surface water retention, regular infiltration reaching the water table at a regular basis, while pollutants absorbing both from water by roots and from the air-dust as windbreaks.

This study has the advantage of having continuously followed up a large number of heavy metals during years, yielding results which shed light to new legislation on open pit rehabilitation and alluvial small scale gold mining, relevant in many countries.

Authorization

This paper was authorized for publication by Twangiza Mining SA authorization later dated December 1, 2023.

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Conflicts of Interest

The authors declare no conflict of interest for this paper.

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