Water quality in the Lisungwi and Kaphamtengo Rivers in Manondo, Central Malawi: Assessment of the impact of artisanal small scale gold mining

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Abstract

Water quality assessment for river systems is important for tracing any changes in quality caused by, among other things, mining activities. Mining activities can be one of the most impactful sources of water contamination. In Malawi, gold deposits occur in the basement rocks of the Lisungwi-Manondo region. As a result, a boom in small scale artisanal mining has occurred as residents have settled in the area. Despite the development of artisanal small scale mining activities, few studies have investigated the water quality of the main rivers in the region (i.e., the Lisungwi and Kaphamtengo Rivers), upon which local residents are highly dependent for daily use. This study provides baseline data for water quality in the region. On-site and laboratory measurements were carried out on the river water samples, to obtain the physio characteristics (e.g. pH, turbidity, electric conductivity) and the major and minor element concentrations of the river water. The data was compared to the regional geology to establish anthropogenic and/or geological impacts on the water quality. The river water has a moderate buffering capacity due to its high alkalinity, along with high Ca, Si, Mg, and Cl concentrations sourced from the gneiss and calcsilicate rocks in the region. Further analysis of the water quality based on the physiochemical parameters, major and trace element concentrations, showed that the river waters were in accordance with guidelines set by the Malawi Bureau of Standards (MBS) and the World Health Organization (WHO) for river water quality, with all analyzed parameters being below the stipulated standards. Our results indicated that the regional geology exerts a significant control on water chemistry, but the mining activities on and along the river water leaves the water in an uncontaminated state.

Keywords: River water, artisanal gold mining, geological control, uncontaminated, Malawi

1. INTRODUCTION

Reports of artisanal gold mining in Malawi date back to the 1930s, and an interest in the exploration of economically significant gold (Au) occurrences persists until today (British Geological Survey, 2009). A few exploration programs focus on previously known Au occurrences. Key sites for further development include the Lisungwi Valley-Kirk Range, the Nathenje region in Lilongwe, and the Dwangwa River in Nkhotakota (Japan International Cooperation Agency [JICA], 2013). However, the progress made on such exploration programs has varied. Despite the widely reported gold prospects, environmental assessments, particularly on the river water, remain highly unreported.

Recently, Malawi has experienced a boom in alluvial/placer gold mining (Malunga, 2012). The main mining areas include Mangochi, Chitipa, Kasungu, Lilongwe, Ntcheu, Neno, and Balaka. Among them, the Ntcheu-Neno-Balaka block, in the Lisungwi Valley-Kirk Range, is the largest hotspot and attracts hundreds of miners, a significant proportion of which are small scale artisanal miners (Catholic Commision for Justice and Peace [CCJP], 2012; Etter-Phoya, 2015). Such mining booms have the potential to ravage landscapes, disturb natural ecosystems, and contribute to the loss of agricultural and farmland. Increased human activities in mining areas can undermine the availability and quality of natural resources such as water (Wilson et al., 2015; Funoh, 2014). Despite the widespread use of groundwater from boreholes in rural areas of Malawi, a significant portion of the population continues to rely on surface water (including rivers) for domestic use such as drinking. Measurements of the chemical composition of these water sources in most areas are either scarce or non-existent (Addison et al., 2020; Mkwate et al., 2017; Sajidu et al., 2007). The risks associated with mining activity are high due to (a) the potential exposure of the population to unsafe water sources, and (b) the inability to monitor the impact of artisanal gold mining on the availability and quality of water resources. Kanyerere et al. (2012) discuss the effects of water contamination by microbial pathogens, physical agents, chemical compounds, and radiologic agents. Such effects include environmental and health concerns for millions of people and can be associated with increased morbidity and mortality, especially in vulnerable populations most at risk of water-related diseases.

Consequently, unregulated gold mining in the country is of great concern for farmers, government officials, and environmental experts.

To address the scarcity of physicochemical datasets of water in Malawian artisanal gold mining hotspots, we conducted measurements in the Lisungwi River in the Manondo area, within the Ntcheu-Neno-Balaka block. Due to widespread artisanal mining activities in the region, we also sampled the Kaphamtengo River, a tributary of the Lisungwi River. Our research addresses the absence of crucial water quality data in the area, where water from the Lisungwi and Kaphamtengo Rivers are used for domestic purposes by local communities.

1.1. Water and socio-economic factors

During the field work activities, observations and verbally communicated information from the locals was obtained and combined with informal reports to have an overview of the river water usage at Lisungwi and Kaphamtengo Rivers. Water from the Lisungwi and Kaphamtengo Rivers is used for domestic purposes. These rivers constitute the main source of water for cooking, bathing, and washing, as well as drinking for local residents and farmed animals. Fertilizers are used on cropland—mainly maize, groundnuts and soybeans—near the rivers to improve yields. The rivers' water levels fluctuate significantly, as attested by layered marks left by high waters during the rainy season and recordings of flooding events. Informal communications with local residents suggested that the quality of the river water was satisfactory, and that no foul taste or coloration had been observed in and outside of the rainy season. High turbidity has been recorded during the rainy season, mainly due to storm water inflow and the mixing of water with sediments. However, once settled, the river water quickly returns to an easily usable form. Despite the absence of stringent community rules to protect water resources, the river water appears to be fit for consumption and daily use, however, scientific evidence to support this and document the river water quality still lacks,

2. LOCATION AND GEOLOGY OF THE STUDY AREA

The study area (i.e., two rivers) is located at the boarder of the Neno, Balaka, and Ntcheu districts in southern Malawi (Figure 1), NE of Blantyre city. The area can be accessed through branching off the M1 road, in a gravel road, about 8 km from the main road. The Lisungwi River forms the boundary between the Balaka and Neno districts, while the Kaphantengo River markes the boundary between Ntcheu and Balaka Districts. The Malawi–Mozambique border lies a few kilometers to the west of the study area. Precambrian metamorphic rock is the dominant lithology in the study area (Rivett et al., 2019). The area's major rock types include granitoids, pegmatite gneiss, and calc-silicates, with abundant quartz and pyrite minerals.

However, the rock types mainly associated with gold mineralization are the biotite gneiss and schist associated with sulphide mineral paragenesis. The two rivers flow through the Kirk Range Valley, along which Au deposits have been identified. An early drilling program carried out in the 1900s identified stockwork mineralization and stringer zones, most of which are structurally controlled, which contain an average 2.7 g/t of Au (British Geological Survey, 2009). In addition to I-type intermediate to felsic intrusions, sulphide assemblages were identified, such as arsenopyrite, pyrrhotite and pyrite. Residual gold has also been reported from the overlying regolith.

Gold occurrence in the region was discovered the 1900s, in stream sediment gravels and sand in a nearby stream, along with the Lisungwi River. Given the nature of the occurrence, the artisanal small scale gold miners extract the gold through excavation of riverbed sand, as well as riverbank sands. The excavated materials are heaped along riverbanks for panning and sieving to collect the gold.

3. MATERIALS AND METHODS

3.1 Sampling and on-site field measurements

The stratified sampling approach was implemented, whereby samples were collected from the upstream to the downstream, at sampling points 1 to 3 km apart. Much as the locations were chosen within a certain distance, the accessibility of the river at some points resulted in the wide range of variation between sampling points. Water was sampled from eight locations on the Lisungwi (L1 to L6) and Kaphamtengo (K1 to K3) Rivers in September 2019. September is one of the months in Malawi's dry season and precedes the driest season of October when temperatures are the highest in the region. The sampling was carried out in dry season to emphasize the degree of contamination since dilution commonly occurs in rainy season (e.g. Tum et al., 2021). Four kinds of samples were collected at each location in pre-rinsed 50 mL plastic polyethene bottles for the following analyses: (i) an unfiltered sample for on-site measurements; (ii) a 0.2 μm polytetrafluoroethylene (PTFE) membrane-filtered, non-acidified sample for anion analyses; (iii) a 0.2 μm PTFE membrane-filtered sample acidified with 1 vol% HNO_3 (ultrapure grade, Kanto Chemicals, Japan) for cation analyses; and (iv) a 0.45 μm PTFE membrane filtered sample for alkalinity titration. For each on-site measurement sample in (i), the measurement was carried out in triplicates to obtain an average. The three latter samples were kept at ~4°C and analyzed at the Laboratory of Environmental Geology, Hokkaido University, Japan.

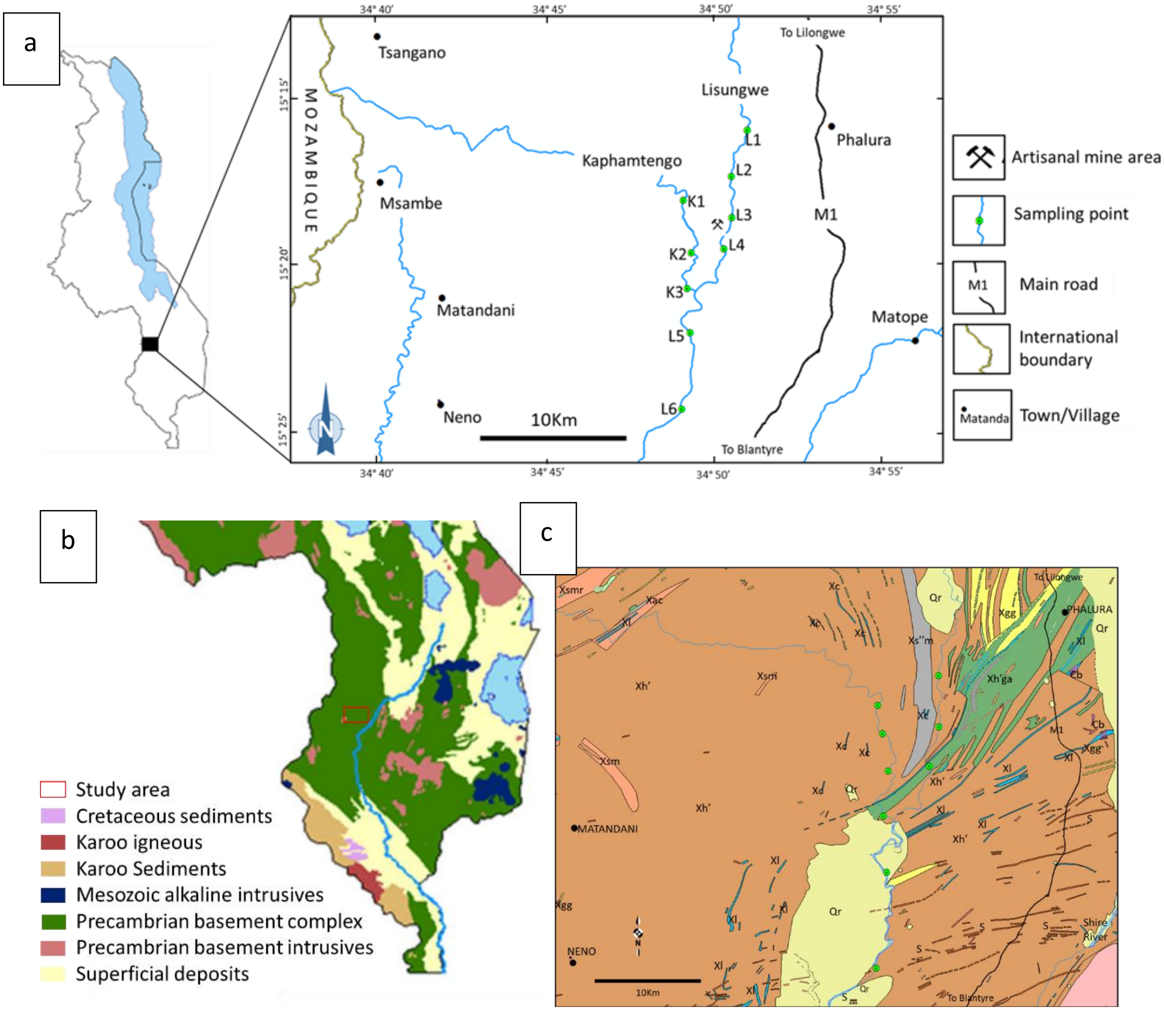

Figure 1: *Location of the study area in Malawi (top), geological map of the study area (bottom left (British Geological Survey, 2019)) and enlarged geological map of the study area showing sampling points as green dots (bottom right).*

The dissolved oxygen (DO), pH, electrical conductivity (EC), turbidity, temperature, oxidation–reduction potential (ORP), and alkalinity of the water samples were measured on-site. Alkalinity was measured by titrating HNO_3 into the 50 mL water samples that had been filtered through a 0.45 µm PTFE membrane filter. The bicarbonate ion (HCO_3^-) concentration was obtained from alkalinity using the Gran function plot method (Rounds, 2006).

3.2 Data and Laboratory Analytical Methods

Non-acidified water samples were diluted 10 times and analyzed for anion concentrations by ion chromatography (Metrohm Advanced Compact IC 861). Anion mixture standard solution 1 (Multi-anion Standard Solution 1, Wako Pure Chemical Industries, Ltd) was used as the calibration standard. Acidified water samples were diluted 40 times to ensure consistency of ionization in the plasma, in order to obtain reliable quantitative data. and the diluted samples were then analyzed for major and trace element concentrations by inductively coupled plasma–atomic emission spectroscopy (ICP–AES; Shimadzu ICPE-9000) and ICP–mass spectroscopy (ICP–MS; Thermo Scientific iCap Qc). Multi-element standard solutions were prepared using a multi-standard solution (Wako Pure Chemical Industries, Ltd.). Ruthenium, Rh, and Ir were used as internal standards for the ICP–MS analyses. Oxide formation during measurements was monitored by the CeO/Ce ratio, which remained below 0.5% to minimize the mass interference of Ba-oxides on Eu. The Geochemist’s Workbench (GWB14) software was used to calculate the charge balance and construct the Piper diagrams for water classification.

4 RESULTS AND DISCUSSIONS

4.1 Physicochemical characteristics of the river water

The physicochemical parameters of the two rivers measured on site are presented in Table 1. All results were compared to the guidelines from the Malawi Bureau of Standards (MBS) and the World Health Organization (WHO) to determine the quality-based use of the water. The pH of the water in the rivers was near-neutral to mildly alkaline for all samples (7.30 to 7.68), in accordance with MBS and WHO standards for stream and river waters. DO values were relatively uniform (with an average of ~7.31 mg/L), although DO at L1 was slightly lower than at other sites. Similarly, EC and temperature were relatively homogeneous, varying from 16.15 to 22.50 mS/m, and from 22.87 to 29.47°C, respectively. The rivers are relatively oxidizing according to ORP values that range from 183 to 282 mV. Turbidity values were similar between sites (22.40 to 41.63 FTU), except in the visibly brown colored water at K1, where turbidity reached 169 FTU. The high turbidity at this site was most likely due to re-construction of a bridge activities that were observed during sample collection. The bridge had been destroyed due to previous flooding events, prompting people to cross through the river directly, thereby contributing to the high turbidity of the river water. Anion concentrations measured in these water samples were all below WHO and MBS standards, and the average charge balance was calculated as ± 12%.

Table 1: *Physicochemical characteristics of the Lisungwi and Kaphamtengo Rivers.*

Site	pH	*DO (mg/L)	EC (mS/m)	ORP (mV)	Turbidity (FTU)	Temp. (°C)	Alkali. (mg/L)	NO_3 (mg/L)	Cl– (mg/L)
K1	7.30	7.45	16.15	282	169	22.87	35.1	14.2	21.2
K2	7.56	7.21	19.11	212	41.6	26.33	50.7	16.6	20.6
K3	7.61	7.14	18.74	234	27.3	26.93	50.7	14.6	29.5
L1	7.57	6.96	22.07	201	35.7	29.47	50.7	12.6	22.4
L2	7.53	7.31	19.82	183	27.5	27.33		12.4	24.0
L3	7.51	7.32	20.14	196	29.5	29.33	50.7	12.4	23.9
L4	7.53	7.65	19.70	242	33.0	23.63		12.2	25.5
L5	7.68	7.33	22.50	247	25.3	24.87	50.7	12.3	27.7
L6	7.51	7.04	21.67	234	22.4	28.70	58.6	12.4	38.8
WHO	6.5-8.5	5.80	10 - 100	200-500	10	18 to 23	20 - 250	50	1 - 100
MBS	6.5-8.5	7.00	10 - 100	-	10	16 to 25	20 - 300	45	1 - 100

*DO: Dissolved oxygen; EC: Electric conductivity; ORP: Oxidation-reduction potential; Temp.: Temperature; Alkali.: Alkalinity; WHO: World Health Organization; MSB: Malawi Bureau of Standards.

4.2 Geological Controls on Water Quality

Understanding the quality of surface waters has been done using various approaches, with the aim of highlighting the controlling factors for their chemistry. Surface waters have a wide range of controlling factors, that range from groundwater quality and compositions, the bedrock of the area and anthropogenic processes such as farming, industrial use and mining. Appello and Postma (2005) summarized the controlling parameters, using plots that compare surface waters from around the world. Besides the major factors, taking into consideration the hydrological cycle highlights the complexity of the factors that affect the surface waters, such as rainfall, mixing of various waters, evaporation and uptake by vegetation among other factors (Pagano and Sorooshian, 2014; Kumambala, 2010). Specifically, the decay of organic matter, weathering, and dissolution of minerals, mixing of different water qualities and anthropogenic activities are the processes that underlie the major factors affecting water quality. Since the amount of organic matter to be taken into consideration at Lisungwi and Kaphamtengo Rivers is very minimal, redox reactions of organic matter are not considered as a controlling factor for the river quality. Furthermore, the main anthropogenic activities that are carried out in the area are domestic use, feeding of cattle and small-scale artisanal mining. However, since these activities are carried at a very small scale and by a small population, anthropogenic factors may not really be controlling the water chemistry at the site. Therefore, that leaves the major controlling factor for the water quality in Lisungwi and Kaphantengo Rivers to be the underlying geology, which allows for interaction with existing bedrock and dissolution of minerals.

Lisungwi and Kaphamtengo Rivers flow through metamorphic rocks. Metamorphic dolomitic marble, minor calcite, granite, and minor diopside occur in the region, in addition to gold-bearing quartz, pyrite among other occurrences. Rock fragments, gravel, sand, and sub-sand are also found in the wider region. Given the mineral composition of the main mineral occurrences in the region, a correlation between the river water and bedrock is investigated.

Major element concentrations of the river water are presented in Figure 2. All concentrations were below MBS and WHO standards, and were relatively similar at all sites. All major elements present in our standard (Al, Ba, Ca, Fe, K, Mg, Mn, Na, Si) were analyzed, but most of them were below the detected limit, therefore those reported in Figure 2 are those whose concentrations were high enough to analyze. Elevated Si concentrations, possibly from the presence of the (Ca)- silicate minerals, in the region, also supported a geological control on the elemental composition of the river water. The Ca concentrations in Kaphamtengo River ranged from 12 to 13 mg/L while in the Lisungwi RLisiver were slightly elevated, with their values ranging from 13 to 16 mg/L. Mg concentrations were within 4 to 7 mg/L in both rivers. Similarly, other major elements such Si and K were within similar ranges in the two rivers. Despite all of the elements being under the recommended standard, a trend in geological control is observed.

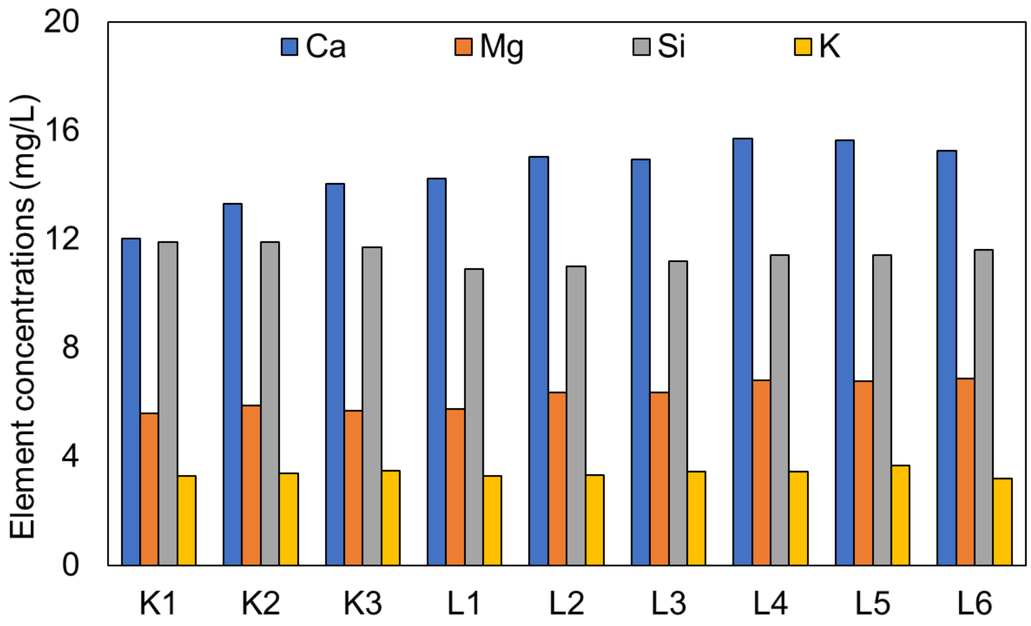

***Figure 2**. Major element concentrations in the Lisungwi and Kaphamtengo Rivers.*

River water (bi)carbonate, Ca, and Mg concentrations vary from 1 to 100 mg/L, with Ca and Mg concentrations being as low as 1 to 5 mg/L, and those beyond 5, commonly being those that are impacted by other factors such as geology (McGowan, 2000). The (bi)carbonate, Ca, and Mg concentrations in the Lisungwi and Kaphamtengo Rivers are suggestive of a strong buffering capacity of the water and are indicative of a dominant geological control on water quality. The Ca and Mg concentration and the highest major elements present in the water, evidently from the interaction of the water with the bedrock which consists of calcsilicates, dolomites and other carbonate rocks. From the major elemental concentrations, it is evident that the regional geology has a significant impact on water chemistry, however, this does not result in contaminated water.

4.3 Concentration of Hazardous Elements

The insight obtained from the major chemistry was then complemented by investigating the trace elements (As, Ba, Cd, Co, Cr, Cs, Cu, Ni, Pb, Sr and Zn), in order to identify any potentially hazardous elements that may have been present in the river waters. All the trace elements that were analyzed had concentrations below 1.5 µg/L, and most of them, except some (discussed later) were below the detection limit. The low concentrations in the water samples show that the water in the Lisungwi and Kaphamtengo Rivers is uncontaminated. Despite the low concentrations, a minor trend was observed for the elements whose concentrations were within observable limits, i.e., As, Cr and Cu. These concentrations, despite being very low, are slightly higher in the Lisungwi River unlike the Kaphamtengo River (Figure 3).

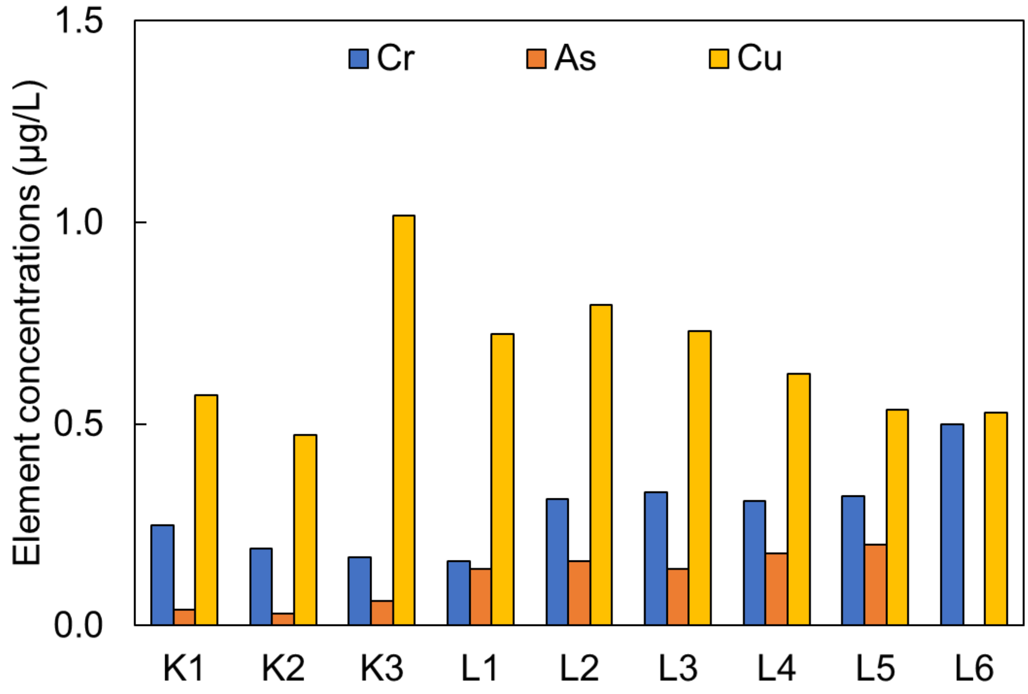

Figure 3: *Trace element concentrations in the Lisungwi and Kaphamtengo Rivers.*

This trend is similar to that displayed by Ca. Although a variation occurs in the two rivers, the difference is nearly negligible, and quite minimal to draw strong conclusions from. This is mainly because the region has mainly similar geology, and this justifies majority of the similarities in the chemistry of the river systems (Figure 1, bottom). The underlying bedrock may just be responsible for releasing more Ca, and possibly As and Cr, that results in the slightly elevated values in the Lisungwi and not Kaphamtengo Rivers. However, given the minimal variation, this trend is highly restrictive to draw major conclusions from at this point. Nonetheless, it is evident, the results presented in this study show that the anthropogenic activities occurring at the two rivers have thus far not influenced the water chemistry in the rivers, therefore, our dataset may be considered a baseline to monitor future changes in land uses and their effect on water chemistry.

The water chemistry was further classified using a piper diagram (Figure 4). Elevated Cl concentrations in the Piper diagram suggest the influence of calcsilicate rocks on water chemistry. The total dissolved salts were about 135 mg/L on average, with high amounts of Ca, Mg and HCO_3. Underlying bedrock mainly controls the water chemistry though dissolution of the existing minerals.

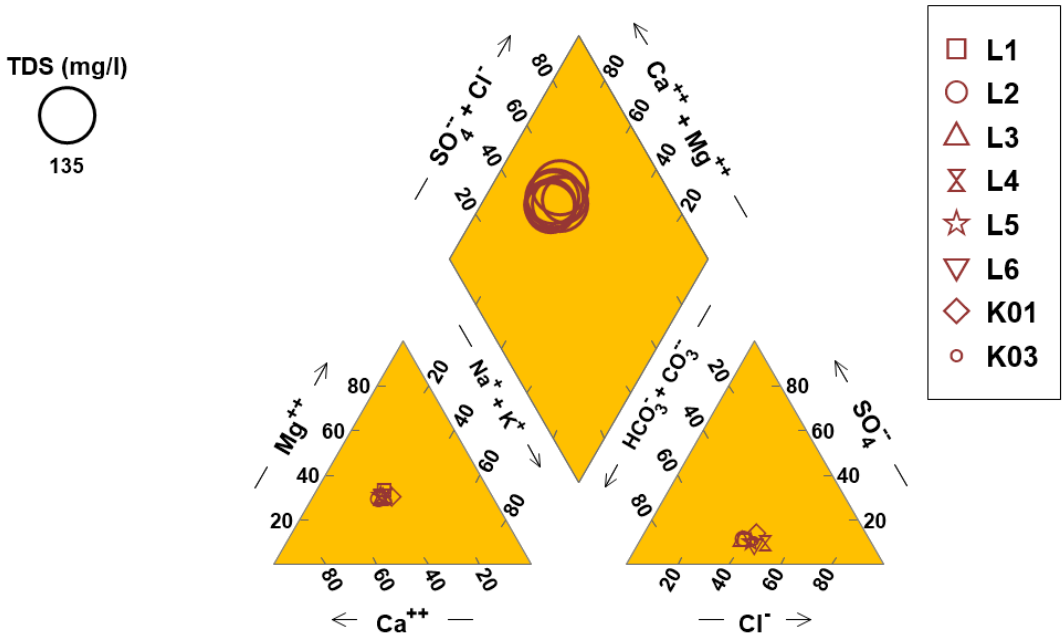

Figure 4: *Piper diagram displaying the chemical compositions of the Lisungwi (L01–L06) and Kaphamtengo (K01–K03) Rivers.*

A comparison of the Lisungwi and Kaphantengo Rivers with other world surface waters is shown in Figure ***5***Figure 5). The plots suggested by (Gibbs, 1970) give a reflection of the nature of groundwater that interacts with the surface water. Na and Cl are ions that are mainly contributed from rainwater, whereas on the other hand, elements like Ca and HCO_3 are a result of dissolution by Ca-silicates, calcite and other carbonate minerals. According to the plots, it is seen that Lisungwi and Kaphantengo Rivers plot almost in the middle of Ca and Na rich waters, but more inclined towards the Ca region, thereby highlighting the impact form dissolution of the underlying minerals. And to complement the possibility of mineral-rock interaction, the Lisungwi and Kaphamtengo Rivers are also high in HCO_3, thereby conquering with the initial suggestion that highlights the mineral dissolution as a major factor controlling the water chemistry.

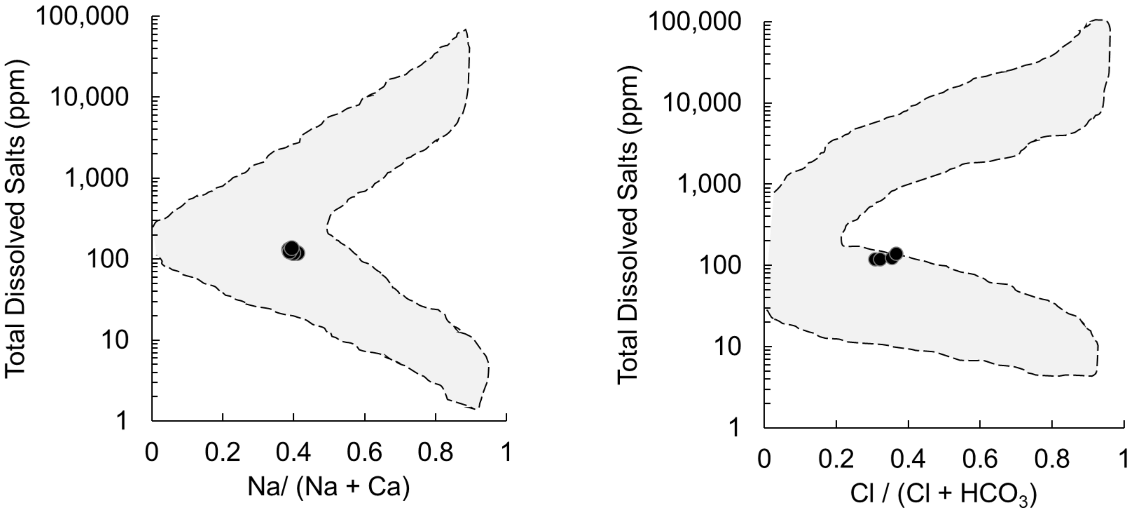

Figure 5: *The chemistry of Lisungwi and Kaphantengo Rivers in comparison with other world surface waters, expressed as a function of total dissolved salts (TDS) and the relative contribution of* Na^{+}*,* Ca^{2+}*, and* Cl^{-} *and* HCO_3^{-} *(Gibbs, 1970).*

It is therefore reasonable to conclude that the water chemistry at the two rivers is controlled by the dissolution of the minerals from the bedrock, thereby giving the water the carbonate nature.

5. CONCLUSIONS AND RECOMMENDATIONS

The potential for gold mining in the Lisungwi catchment area warranted an environmental study to provide background data on river water quality. The Lisungwi and Kaphamtengo Rivers flow through metamorphic rock that currently hosts widespread artisanal gold mines. Alluvial sediments containing gold are collected using buckets and panned multiple times to extract gold. Although the land is slightly disturbed, evidence for no contamination was seen based on the elemental composition of the river water, with most metal concentrations below the WHO standards. Physicochemical parameters were also in line with natural river water that had not been contaminated by mining activities. Potential contamination by other anthropogenic activities, such as farming and bathing, were also explored in our study. We found that the water did not appear to be contaminated by anthropogenic activities, likely because the overall use of the rivers for these activities was low, and because any potential contamination may have been quickly transferred downstream.

The Lisungwi and Kaphamtengo Rivers are important rivers for the livelihoods of the people in the region and hence any developments in the region that may affect the river quality should be closely monitored. At the moment, the extraction of gold by the artisanal small scale gold miners is still not contaminating the river water quality. However, due to growing demands for gold in the region, it is highly recommended that environmental assessments be carried out in the region every now and then to ensure that the river remains uncontaminated even as the mining activities grow.

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