GRÓ Land Restoration Training Programme
Árleynir 22, 112 Reykjavik, Iceland

Final Project Report 2023

EVALUATION OF STREAM HEALTH TO MEASURE MINING IMPACT

Chimwemwe Nelson Bandazi
Department of Mines
P.O. Box 251, Lilongwe, Malawi
nbandazi@gmail.com

Supervisor
Dr Jacob Matthew Kasper
Agricultural University of Iceland
jacob@lbhi.is

ABSTRACT

Mining activities exert significant environmental impacts, including on aquatic ecosystems. This study investigated the impacts of human activities, particularly coal mining, on stream ecosystem health in the Nkhachira coal mine area of northern Malawi. Water physicochemical parameters and aquatic macroinvertebrates were assessed at five sampling sites located upstream and downstream of the mine. The Canonical Analysis of Principal Coordinates (CAP) revealed significant differences in physicochemical parameters among the site categories, with downstream sites exhibiting higher levels of pollutants such as sulphates. Aquatic macroinvertebrates were evaluated using the Mini-KASS index, indicating stressed ecosystem health with warning-level Average Score per Taxon (ASPT) scores. The analysis of macroinvertebrates in relation to water quality and biotopes underscored the impact of human activities in the area, showing both positive and negative associations. Biotope assessments demonstrated that habitat diversity partly influenced macroinvertebrate communities, with stone biotopes positively correlated with certain functional feeding groups. The study highlights the urgent need for improved environmental monitoring and management around the mining site to mitigate ecological impacts. The findings underscore the importance of addressing water quality and biotic aspects in conservation strategies for stream ecosystems in the area. Further investigation into the elevated sulphate levels and decreased pH is recommended for a comprehensive understanding of water pollution risks.

Key words: aquatic macroinvertebrates, stream ecosystem, water quality, environmental monitoring, mining impacts

This paper should be cited as:

Bandazi C N (2023) Evaluation of stream health to measure mining impact. GRÓ Land Restoration Training Programme [Final project]
https://www.grocentre.is/static/gro/publication/862/document/bandazi2023.pdf

TABLE OF CONTENTS

1. INTRODUCTION 5
1.1 Project goal 6
1.2 Project objectives 6
2. LITERATURE REVIEW 6
2.1 Impacts of mining on the environment 6
2.2 Assessment of aquatic ecosystem health using macroinvertebrates 7
2.2.1 Upstream and downstream comparisons 7
2.2.2 Different responses to mining induced disturbances 7
2.2.3 Aquatic invertebrate assessment approaches 8
2.2.4 Area adapted biotic indices 8
2.3 Biotope assessment in interpretation of macroinvertebrates data 9
2.4 Water quality measurements in macroinvertebrates studies 9
2.4.1 Effect of water quality on aquatic invertebrates 9
3. METHODS OF STUDY 10
3.1 Study area 10
3.2 Water, macroinvertebrate, and biotope sampling and analysis 11
3.2.1 Water and environmental parameters 11
3.2.2 Aquatic Macroinvertebrates 12
3.2.3 Classification to functional feeding groups 13
3.2.4 Biotope assessment 13
3.3 Analysis and interpretation of data 14
4. RESULTS 14
4.1 Water and environmental parameters 14
4.2 Aquatic macroinvertebrates 16
4.2.1 Macroinvertebrates response to physicochemical properties of water 17
4.3 Biotope assessment 19
4.4 Macroinvertebrates and biotopes 20
5. DISCUSSION 21
5.1 Classification into upstream and downstream sites 21
5.2 Physicochemical parameters and site distinction 21
5.3 Macroinvertebrate metrics 22
5.4 Macroinvertebrates and response to water quality 22
5.5 Macroinvertebrates and biotopes 22
6. CONCLUSIONS 22
ACKNOWLEDGEMENTS 24

LITERATURE CITED 25
APPENDICES 32
Appendix I Score Assignment for Taxa in MiniKASS Based on Sensitivity to Water Pollution 32
Appendix II: Bar plots of average values of the studied parameters 33
Appendix III: Site pictures 35

1. INTRODUCTION

Despite its relatively small surface footprint, mining dramatically impacts the environment (Ritchie & Roser 2013; Ritchie et al. 2020; Maus et al. 2022; Ritchie et al. 2022; Witchalls 2022). Mining activities severely impact aquatic components of biophysical environments (Punia & Singh 2021; SME 2023). To examine the impacts of mining, environmental variables are measured by several approaches (Ogundele et al. 2021; Saini et al. 2022). A direct assessment of physicochemical parameters is often an effective way of measuring the impact of mining on streams and rivers (INAP 2009). Biological assessment is effective in measuring how changes in the physical or chemical composition of water bodies affect ecosystem health and functionality (EPA 2011; International Network for Acid Prevention (INAP) 2009). A common approach to the biological assessment of aquatic ecosystem health is to study aquatic macroinvertebrates within the impacted drainage channels because they are mostly directly affected by water pollution and indicate a biological community of high integrity (Girgin et al. 2010; EPA 2011).

The Karonga district in northern Malawi has seen rising interest in mining over the past decade especially with regards to uranium and coal (Kamlongera 2013; Business & Human Rights Resource Centre 2018). The district has a total land area of 3,355 square kilometres. An investigation in 2016 reported shortfalls in the monitoring of environmental impacts of mining, particularly around the coal mines in the district (Rall 2016). One of the coal mines in the Karonga district investigated was the Nkhachira Coal Mine located within the administrative region of T.A. Kayelekera under Paramount Chief Kyungu. Among the issues highlighted was the lack of strategies on prevention of watercourse pollution from the mine (Rall 2016). Despite the pertinence of issues raised in the report, there has seemingly been no effort to investigate the effect of the mine on the environment, particularly on water drainage channels.

The geologic environment of the area results in some economic mineral deposits. As with most of Malawi, the Nkhachira area is underlain by the igneous and metamorphic basement complex of Precambrian origin (Carter & Bennet 1973; Nkhoma 2006). The area is overlain by Karoo sediments forming the North Rukuru sandstone and shale formations (Nkhoma 2006). Medium and fine-grained sedimentary rocks derive the predominant soil types of the area, which are Ferralitic Latosols (Ferrasols, Food and Agriculture Organisation 2014) or Haplic Lixisols according to the FAO/UNESCO System of Soil Classification (Nkhoma 2006). Soils around the mine are highly weathered and leached with moderate to medium sub-angular block structure. Pyrite is present in reduced-facies arkose intersections that are associated with the carbonaceous debris within the wider geologic area (Nkhoma 2006).

The mine is close to Kaziwamyelero stream, a tributary of Chaphwasha river that flows into the Sere river (Fig. 1). The Sere river in turn flows into the North Rukuru river, one of the major rivers of Malawi, which flows into Lake Malawi. The Nkhachira Coal Mine is near the Kayelekera Uranium Mine, the largest scale mine in Malawi, that has a long running environmental monitoring programme. While the environmental impact of Kayelekera has long been monitored, the environmental impact of Nkhachira has received little attention (Rall 2016).

It is therefore necessary to understand the impact of Nkhachira Mine on the environment. Aquatic macroinvertebrate assessment is a good indicator of stream ecosystem health and can be generalised to understand the impact of the mine on the surrounding environment (Munyika et al. 2014; Raphahlelo et al. 2022; UNEP 2022). Interpretation of macroinvertebrate

assemblages is enhanced by the study of biotopes in an area because these often provide different substratum, hydraulic and thermal conditions for the taxa (Dallas 2007, 2021). Biotopes are spatially distinct in-stream flow environments characterised by specific hydraulic and substrate attributes and can be considered as community habitats (Rowntree & Wadeson 1999). This project was designed to assess the water drainage channels near the Nkhachira coal mine to determine the effect of the operation on the surrounding aquatic environment.

1.1 Project goal

The goal of the project is to assess stream condition around the Nkhachira mine to determine aquatic ecosystem health.

1.2 Project objectives

The objectives of the proposed project are as follows:

- Assess the aquatic macroinvertebrates in streams near the Nkhachira Coal Mine.
- Evaluate aquatic macroinvertebrate availability in relation to biotopes in the study area.
- Evaluate the relationship between water physicochemical properties and macroinvertebrate metrics.

2. LITERATURE REVIEW

2.1 Impacts of mining on the environment

Mining impacts the biophysical environment due to activities like blasting, earth movement, materials haulage and crushing, and generation of large volumes of waste (Hustrulid et al. 2013; Spitz & Trudinger 2019). Surface and groundwater contamination from solid particulates and chemical contaminants, removal of vegetation and soil which contributes to erosion and siltation are some examples of the ways in which these activities affect the biophysical environment (Darling 2011). These activities further affect the environment through land degradation, atmospheric emissions of dust, and the presence of potentially toxic wastes in rock dumps or tailings storage facilities (Agboola et al. 2020; Worlanyo & Jiangfeng 2021). These effects largely depend upon the nature of the ore under extraction, mining methods for example strip or adit mining, site infrastructure and management practices (Spitz & Trudinger 2019).

The biggest impacts of mining include those on aquatic systems (USGS 2018), with erosion due to overburden removal and other earthworks contributing large sediments to water bodies (Spitz & Trudinger 2019). In mining, large areas of vegetation are cleared and vast soil and rock volumes are removed. Since topsoil is one of the most erodible materials, it usually ends up in watercourses where it can cause short or long-term degradation of aquatic habitats. Erosion of heaped topsoil or waste rock piles transports sediments to streams which leads to increased turbidity and reduces light for photosynthesis by aquatic plants. Increased water sediment loads smother benthic organisms and eliminate important food sources for predators, compromising available fish habitats (Johnson et al. 1998). Some of the deposited sediments become toxic due to their metallic contents and/or due to sulphide oxidation (Spitz & Trudinger 2019), and these disturbances can further reduce water quality through the acidification which further oxidises ferrous to ferric iron (Marcus 1997).The processes by which coal mining affects aquatic environments are largely similar, however due to the sedimentary nature of coal

deposits, there may be some differences in predicting its environmental effects compared to those of hard rock mining (INAP 2009).

Despite the negative effects, mining remains an important primary industry for production of raw materials (World Bank 2020). Practicing good environmental management around mining sites to monitor and mitigate these negative environmental impacts is an apt approach (GRI 2022). It is sensible to consider coal mining operations in addressing environmental and societal consequences of mining amid efforts to eliminate thermal coal, which is coal that is suitable for electric power generation, to slow down climate change.

2.2 Assessment of aquatic ecosystem health using macroinvertebrates

It is important to assess aquatic ecosystem health to determine the impacts that mining has on biological diversity because this is a good proxy of ecosystem functioning (Rico-Sánchez et al. 2022). Aquatic macroinvertebrate communities are good indicators for the overall health of freshwater ecosystems, and these are often used to monitor the ecological conditions of streams impacted by mining (Ali et al. 2018; Bae et al. 2021; Ouma et al. 2022; Rico-Sánchez et al. 2022). These invertebrates can also be easily monitored with data that is statistically useful (Knight Piesold 2006). Macroinvertebrates are classified into functional feeding groups based on morphological and behavioural attributes in food acquisition (Herman & Nejadhashemi 2015; Cummins 2018; Mangadze et al. 2019) and they are assigned to different roles in stream ecosystem processes such as grazers, shredders, gatherers, feeders, and predators (Wallace & Webster 1996). Functional feeding group ratios such percentages of shredders, collectors and scrapers or filterers are indicators of stream health and ecosystem functioning. For example, shredders were sensitive to water quality deterioration thus, a lower abundance ratio of this taxonomic group represents a good indicator of human impacts on ecosystems (Mangadze et al. 2019).

2.2.1 Upstream and downstream comparisons

Upstream and downstream comparisons are used to study the impacts that human activities like mining have on natural stream ecosystems (Bergey & Ward 1989; Ko et al. 2020; Shakya et al. 2021). This approach has been applied in the biomonitoring of aquatic environments with some focus on macroinvertebrates (Bowles et al. 2020). It greatly simplifies environmental monitoring for the detection of river contamination because it is cheaper and simpler than long term monitoring (Dolan & El-Shaarawi 1989). An application of this approach was used by Shakya et al. (2021) who demonstrated how macroinvertebrate communities impacted by mining pollution compared to sites that were upstream and further downstream of the polluted site. The authors were able to demonstrate not only changes in community composition but also changes at the genetic level among the downstream taxa in comparison to those that were upstream.

2.2.2 Different responses to mining induced disturbances

Macroinvertebrate communities respond differently to mining induced disturbances in stream ecosystems (Timpano et al. 2018; Steyn et al. 2019; Bae et al. 2021). Species richness, the number of different species represented in an ecological community, is negatively impacted by mining through effects like increased acidification of water due to sulphate sediments and increased osmoregulation stress (Bae et al. 2021). According to Bae et al. (2021), functional feeding group ratios were lower or non-existent for grazer-scrapers in the mining affected

streams indicating that the impacts of mining varied among functional groups. Community stability, which is the ability of a community to recover from disturbances to its structure or function, decreased in the mining affected streams.

Sulphate leaching increases freshwater salinisation which affects aquatic invertebrate communities in mining regions (Timpano et al. 2018). Ephemeroptera (Mayflies) were the most affected group due to the salinity as evidenced by declines of species richness and diversity with increased salinity. Some groups such as Plecoptera (stoneflies) were less affected by the salinity and even showed signs that they benefited from the increased salinity. Steyn et al. (2019) used different metrics including macroinvertebrate biotic indices to interpret effects of toxicity from treated acid mine drainage (AMD), which is usually water pollution resulting from oxidation of sulphide minerals. The community structure of the macroinvertebrates was shown to change with salinity and toxicity from the AMD.

2.2.3 Aquatic invertebrate assessment approaches

Different approaches are used for assessing aquatic macroinvertebrates in streams for example full enumeration and rapid bioassessment (Pence et al. 2021). Either approach is acceptable depending on the situation and aims of the study, however, some trade-offs exist between the approaches as reported by Pence et al. (2021) who used rapid bioassessment to detect changes in the alteration of communities along stream biophysical gradients. Full enumeration was shown to be more useful for complete community characterisation. In full enumeration, a key step is usually species identification, however this is often not done because it requires a high level of taxonomic expertise (Carew et al. 2013), as such rapid bioassessment is sufficient in many stream ecosystem health assessments.

2.2.4 Area adapted biotic indices

Various methods of stream health assessments have been evaluated in the sub-Saharan Africa region (Dallas 2021; Masese et al. 2023). Diversity and richness indices were compared with region specific biotic indices including the South African Scoring System version 5 (SASS5), the Tanzanian River Scoring System (TARISS), and a macroinvertebrate-based index of biotic integrity (M-IBI) developed for the Ethiopian highlands (Masese et al. 2023). These studies have demonstrated the need to curate indices and protocols to suit local conditions in a study area. The need for the assessment of macroinvertebrate taxa tolerance was also demonstrated to be vital in the adaptation of biotic indices for local use.

The SASS5 is a widely used bioassessment method of stream health in South Africa (Dickens & Graham 2002; Knight Piesold 2006; Masese et al. 2023). It is a rapid assessment method based on the presence of major invertebrate families that are assigned weighted scores depending on their sensitivity and tolerance to changes in stream condition. Information on biotope characteristics is important for the enhancement of interpretability of the biomonitoring data. The method was developed specifically for macroinvertebrate studies in South African streams but is adaptable to other parts of Africa where similar conditions, particularly taxa, are present. A simplified version of the SASS5 system was developed for the Kayelekera region of Malawi, the Mini-Kayelekera Scoring System (Mini-KASS, Knight Piesold 2006). The Mini-KASS system is optimised for identification of taxa with minimal training. The Mini-KASS system will be utilised in this study because it was developed specifically for the area in which the project will be undertaken and does not require specialised training in higher level taxa identification.

2.3 Biotope assessment in interpretation of macroinvertebrates data

Biotope assessment can enhance the interpretation of results from aquatic invertebrate studies (Dallas 2007; Staudacher & Füreder 2007), because biotopes are closely linked to biological diversity (Phillips 2017). Structural and functional organisation of macroinvertebrate assemblages can be positively influenced by the available habitats (Staudacher & Füreder 2007). In addition, differences in macroinvertebrate assemblages have been observed to be greater among different biotopes than between study sites (Dallas 2007). Taxonomic richness varies among different biotopes and there are differences in community structure among waterfalls, cascades, pools, and riffles (Baker et al. 2016, 2017). Different biotope attributes are vital in the understanding of macroinvertebrate communities in tropical running rivers, as it has been shown that macroinvertebrate communities exhibited different preferences of depth, habitat shade and substrate, and flow velocity (Muñoz-Mas et al. 2019).

2.4 Water quality measurements in macroinvertebrates studies

Interpretation of macroinvertebrate assessment data is enhanced by availability and analysis of water quality data (Tampo et al. 2021; Ouma et al. 2022; Masese et al. 2023). Some of the negative impacts of mining on freshwater ecosystems like dissolved metal pollution, pH changes and increased sediments (which can be both sinks and sources of heavy metals), affect aquatic macroinvertebrate communities (Ouma et al. 2022). Hu et al. (2022) looked at how macroinvertebrates responded to key water quality parameters. The researchers evaluated how land use reduced water quality and found this had negative implications on macroinvertebrate composition and diversity and subsequently indicated poor ecosystem health.

The effects of water quality on macroinvertebrate assemblages for example structure and diversity have been demonstrated in studies using multivariate analyses (Rico-Sánchez et al. 2022; Duque et al. 2022). Mining activities were shown to impair macroinvertebrate communities in association with water quality parameters. These results suggest that biomonitoring can be used to detect pollutant effects on sensitivities of different taxonomic groups to different chemical stressors in aquatic ecosystems. This can present a cost-effective option for biomonitoring in resource constrained regions (Rico-Sánchez et al. 2022).

2.4.1 Effect of water quality on aquatic invertebrates

The physicochemical composition of water affects aquatic macroinvertebrates in different ways (Dallas 1995; Brooks et al. 2012). In addition to provision of the right living conditions in aquatic systems, temperature impacts nutrient and toxin availability, oxygen saturation, metabolic rates and may affect duration of the life cycle stages of the invertebrates (Dallas 1995). High levels of suspended solids and turbidity restrict the amount of sunlight reaching primary producers in aquatic ecosystems affecting food availability to higher trophic levels, the sediments also smother benthic organisms and cover gravels that can be important habitats for aquatic organisms (Dallas 1995; Johnson et al. 1998; Brooks et al. 2012). Suspended solids can adsorb toxins or nutrients affecting aquatic life in both positive and negative ways. Macroinvertebrate taxa tolerate dissolved oxygen at saturation levels higher than 10 to 25%, and low dissolved oxygen (DO) levels can lethally affect communities of macroinvertebrates (Connolly et al. 2004). According to the same report (Connolly et al. 2004), dissolved oxygen also affects reproduction at the sublethal level as evidenced by a reduction in the emergence of insect taxa at intermediate DO levels.

pH can affect primary production in addition to having a direct effect on aquatic macroinvertebrates for example the increase of physiological stresses on the organisms by increased energy requirements (Dallas 1995; Brooks et al. 2012). Total dissolved solids and electrical conductivity are usually correlated in water and these mainly affect aquatic macroinvertebrates at the juvenile stages especially in upper mountain streams where organism stress levels are generally reduced (Dallas 1995; Brooks et al. 2012). Sulphate reduces dissolved oxygen availability, increases water salinity, alters water body geochemistry through precipitation of metals to form metal sulphides which also reduces pH, and it ultimately disturbs the diversity and composition of aquatic communities leading to dominance of high sulphate tolerant taxa (INAP 2009).

3. METHODS OF STUDY

3.1 Study area

The area of study is the Nkhachira coal mine located in Karonga district in northern Malawi (Fig. 1). It is a small-scale mining operation with a monthly production of less than 800 metric tonnes having had a historical production of about 7,000 metric tonnes per month (Hancox 2016; Consolidated Coal Mining Industries Company Limited 2020). It is currently an adit type of mining operation, having previously operated as a strip mine between 2013 and 2016. The mine licence area covers 3.5 km^2. The mining site is located 55 kilometres west of Karonga district headquarters and it falls under village headman Kayelekera (Knight Piesold 2006). The site is 8 kilometres south of the road between Karonga and Chitipa.

Mean annual temperature in the area ranges from 18°C to 28°C and mean annual rainfall is between 800mm and 1200mm (Nkhoma 2006; Knight Piesold 2006). Subsistence farming is the predominant land use within the area and the 'slash and burn' type of agriculture was reported to be common (Nkhoma 2006). Cultivation along the seepage wetlands is also common in the area (Nkhoma 2006). The major water drainage basin for the area is the North Rukuru basin which comprises several drainage channels that are reliable water sources for local communities (Nkhoma 2006). The drainage channels include the north Rukuru river which had a maximum flow of about 8 m^3s^{-1} for June-July 2023 (The GEOGloWS Initiative 2023).

Data were collected at five sampling sites (0.5 m from riverbank) selected based on their location upstream or downstream of the mine (Table 1 and Fig. 1). Site coordinates were recorded using a Garmin GPSmap 60Cx device. Kaziwamyelero stream, a small seasonal (dries up in cold season) mountain headwater stream originating from the Musisi Forest reserve, flows through the mine. Site UPS1 was upstream of the mine on Kaziwamyelero stream and DWS1 was downstream of the mine on the same stream. Kaziwamyelero is a tributary of the Chaphwasha river which passes to the east of the mine from the Musisi Forest. Site DWS2 was downstream of the mine on the Chaphwasha river, a perennial tributary of the Sere River. The Sere River, with a maximum flow of about 1 m^3s^{-1} for June-July 2023 (The GEOGloWS Initiative 2023), is a perennial tributary of the major river in the area, the North Rukuru, and it flows north of the mine. Site UPS2 was upstream of the mine on the Sere River and DWS3 was downstream of the mine after the confluence of the Chaphwasha and Sere rivers.

Table 1. Sampling locations for the study of aquatic invertebrates and water physicochemical parameters with distances to the mine in meters.

Site	River or stream	Description	Latitude (S)	Longitude (E)	Distance from mine
UPS1	Kaziwamyelero stream	Upstream	10.0086441°	33.6728285°	500
DWS1	Kaziwamyelero stream	Downstream	9.9981609°	33.6734182°	700
DWS2	Chaphwasha river	Downstream	9.9741154°	33.6811508°	1400
DWS3	Sere river	Downstream	9.9734460°	33.6855833°	1960
UPS2	Sere river	Upstream	9.9703978°	33.6858206°	2560

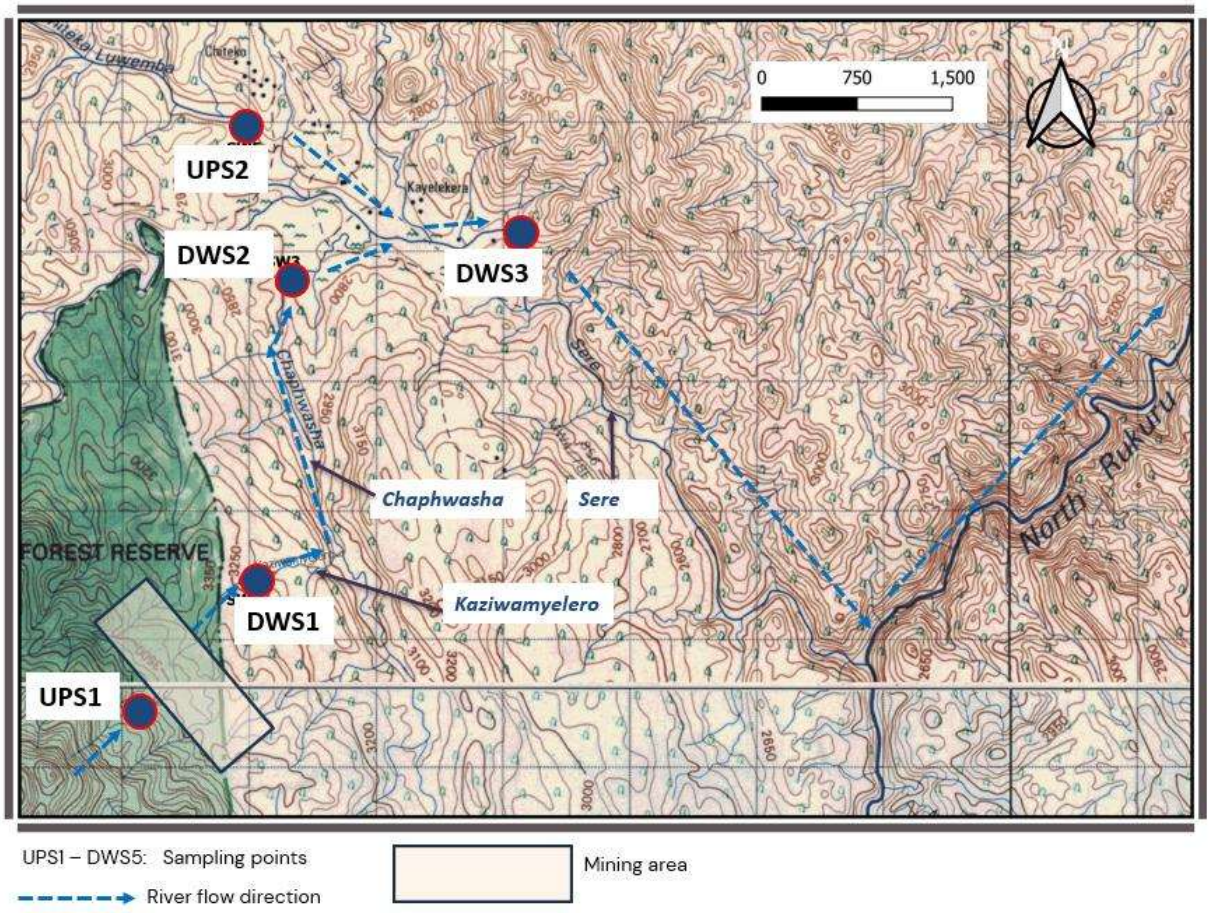


Figure 1. Map of study area with sampling locations (blue-red dots, UPS1 to DWS3), river flow directions (blue arrows), and location of the Nkhachira coal mine (rectangle).

3.2 Water, macroinvertebrate, and biotope sampling and analysis

3.2.1 Water and environmental parameters

Water and environmental parameters recorded at each site included pH, electrical conductivity (μScm^{-1}), temperature (°C), total dissolved solids (ppm), all recorded by a Hanna Combo meter HI98129; dissolved oxygen (ppm) measured with a Lovibond SD 400 Oxi L water testing probe; and turbidity (NTU) recorded by a Hanna turbidity meter HI98703-01. The parameters were recorded at a depth of 0.5 meters. Water samples were collected in 100 mL bottles for laboratory analysis of total suspended solids (ppm) and sulphates (ppm). Total suspended solids

were measured by filtration and gravimetric weighing of the filter papers, whereas sulphates were measured by an ultraviolet spectrophotometer.

3.2.2 Aquatic Macroinvertebrates

Aquatic macroinvertebrates were sampled using the Mini-KASS method that was developed for the area in 2006 (Knight Piesold 2006). The method uses the availability and estimated abundances of macroinvertebrates to determine stream health and is based on the sensitivity of the macroinvertebrates to water quality. Estimated abundances were assigned codes ranging from A to D, but one was used where one individual was counted. A represented a range of two to ten individuals, B represented 10 to 100 individuals, C represented 100 to 1,000 individuals, and D represented over 1,000 individuals.

Sites were sampled between 17 May and 12 July 2023 including the transitional period from the hot wet to the cold dry season, and the cold dry season. Biological samples were collected with a kick net in areas assumed to have the best macroinvertebrate habitats, which are usually stony areas, with high water flows and areas of the stream whose sides were vegetated. At each sampling site, five-minute samples were collected with the kick net to scoop out macroinvertebrates from the water using feet and fingers to dislodge them from biotopes. The macroinvertebrates were then transferred into white trays with clean water for easy identification. Forceps and a magnifying glass (where necessary) were used to pick out, identify and transfer the macroinvertebrates to the Petri dishes from the trays where further identification was done, when required.

The weighted scores for the identified taxa as well as the total number of available taxa were summed up and converted to average score per taxon (ASPT) figures (equation (1)). For the Mini-KASS system, results are divided into three classifications showing the level of impairment (Knight Piesold 2006). The three classifications are as shown in Table 2.

$$\text{Average Score per Taxon (ASPT)} = \frac{\text{Total weighted score}}{\text{Total No. of Taxa}} \quad (1)$$

Table 2. Classification of impairment level with average score per taxon (ASPT) scores (Knight Piesold 2006).

ASPT	Indicator
>6	Unimpacted
4-6	Warning
<4	Impacted

In addition to these classifications, total scores were generated based on the number of taxa recorded and their sensitivity to water quality deterioration. Low scores were assigned to taxa that have high resistance to pollution and high scores were assigned to those taxa that are susceptible to pollution (Dallas 1995) (Appendix I).

Margalef richness index (Margalef 1958) and Simpson's diversity index (Simpson 1949) were calculated to analyse taxonomic richness and diversity respectively through the following equations:

$$\text{Margalef richness index (d)} = \frac{(\text{S} - 1)}{\ln \text{N}} \tag{2}$$

where S is the number of taxa and N is the number of individuals or the abundance. A higher Margalef index value means there is a high richness of taxa while a low value indicates lower taxonomic richness.

$$\text{Simpson's diversity index (D)} = 1 - \sum_{i=1}^{S} \frac{n_i(n_i - 1)}{N(N-1)} \tag{3}$$

Where n is the number of individuals in each taxonomic group and N is the total of all individuals in all the taxonomic groups.

3.2.3 Classification to functional feeding groups

The observed taxa were classified into different functional feeding groups as shown in Table 3 (Texas Commission on Environmental Quality 2014; Masese et al. 2014; Cummins 2021). The four major functional feeding groups identified were collectors, scrapers, predators, and shredders. Information about the higher taxonomic levels of some of the taxa was needed for proper assignment into functional feeding groups, thus they remained unclassified for the analysis.

Table 3. Classification of macroinvertebrates into functional feeding groups based on literature (Texas Commission on Environmental Quality 2014; Masese et al. 2014; Cummins 2021)

Collectors	Scrapers	Predators	Shredders	Unclassified
Baetidae	Psephenidae_waterpennies	Naucoridae	Potamonautidae	Trichoptera_caseless
Oligochaeta	Psephenidae_otherbeetles	Notonectidae	Tipulidae	Trichoptera_cased
Caenidae	Heptageniidae	Gerridae		Corixidae
Polymitarcyidae		Hydrometridae		
Leptophlebiidae		Veliidae		Ceratopogonidae
Simuliidae		Anisoptera		Mollusca
Culicidae		Zygoptera		
Chironomidae		Hydracarina		Plecoptera
		Tabanidae		

3.2.4 Biotope assessment

Biotopes were classified according to particle size distribution based on the description in Knight Piesold (2006) that was adapted from Rowntree & Wadeson (1999), and vegetation. Habitat quality was therefore assessed by sampling marginal vegetation out of current (stream edge vegetation), vegetation in current (hanging into or growing in current), bedrock, stones in current and sediments. The abundances of specific habitats were weighted based on particle sizes to develop the biotope condition score (Table 4). Stones-in-current had the highest weight because they are regarded as the best habitats for aquatic invertebrates (Knight Piesold 2006).

Table 4. Biotope (habitat) condition assessment table (Knight Piesold 2006). The highest weight (5.0) applied to stones-in-current as this is regarded as the best biotope for aquatic macroinvertebrates. Vegetation, sand, and mud biotopes are regarded as poor biotopes for the macroinvertebrates.

Biotope	Weight
Stones-in-current (SIC)	5.0
Stones-out-of-current (SOOC)	3.0
Bedrock (B)	2.0
Vegetation in-current (VIC)	0.5
Vegetation out-of-current (VOOC)	2.0
Submerged vegetation (SV)	2.0
Gravel (G)	3.5
Sand (S)	1.0
Mud (M)	0.5

3.3 Analysis and interpretation of data

Statistical analyses were performed to determine the impact of the mine on water and aquatic macroinvertebrates in the surrounding water channels (Alavaisha et al. 2019; Edegbene et al. 2022). Canonical analysis of principal coordinates (CAP) was used to group the sites according to water quality to check the impacts of mining on upstream and downstream sites. To further test the differences in water quality between the sites, the permutational multivariate analysis of variance (PERMANOVA) test was undertaken. Canonical correspondence analysis (CCA) identified potential correlations between the macroinvertebrates and water quality parameters among the sites. The test was also used to check the correlations between macroinvertebrates and the quality of the biotopes. Since macroinvertebrates data was coded into the estimated abundances, minimum abundances in each category, between A and D, were used (section 3.2.2). This approach was taken to avoid the overestimation of taxa, but it also meant that statistical analyses of the invertebrate data were done on rough estimates of the respective taxonomic abundancies. All statistical analyses were conducted using R 4.4.2 (R Core Team 2022). CAP analysis was conducted with the BiodiversityR package (Kindt & Coe 2005), PERMANOVA and CCA analyses were conducted using the vegan package (Oksanen et al. 2022). In addition, correlation tests were conducted that included Spearman's correlation conducted using the corrplot package (Wei & Simko 2021), a correlation matrix of functional feeding groups (FFG) with biotopes was produced using the cor function in R. ggplot2 and GGally were used to plot FFG abundance and biotope plots (Wickham 2016; Schloerke et al. 2021). Other packages used in the analyses were MASS (Venables & Ripley 2002), Tidyverse (Wickham et al. 2019) and dplyr (Wickham et al. 2023).

4. RESULTS

4.1 Water and environmental parameters

The canonical analysis of principal coordinates (CAP) showed clustering of points based on their classification as upstream or downstream sites in relation to the mine (Fig. 2). Permutational multivariate analysis of variance (PERMANOVA) showed a statistically significant difference between the upstream and the downstream sites ($F = 8.1$, $p = 0.001$, Table

5). Sites DWS1 and DWS2 show the greatest distinction in terms of the physicochemical parameters of water measured at the sites. Site DWS1 shows the most distinction in relation to all the other sites. The highest levels of electrical conductivity, total dissolved solids and sulphates were recorded at this site (Table 6). The site also had the lowest average pH of all the sites.

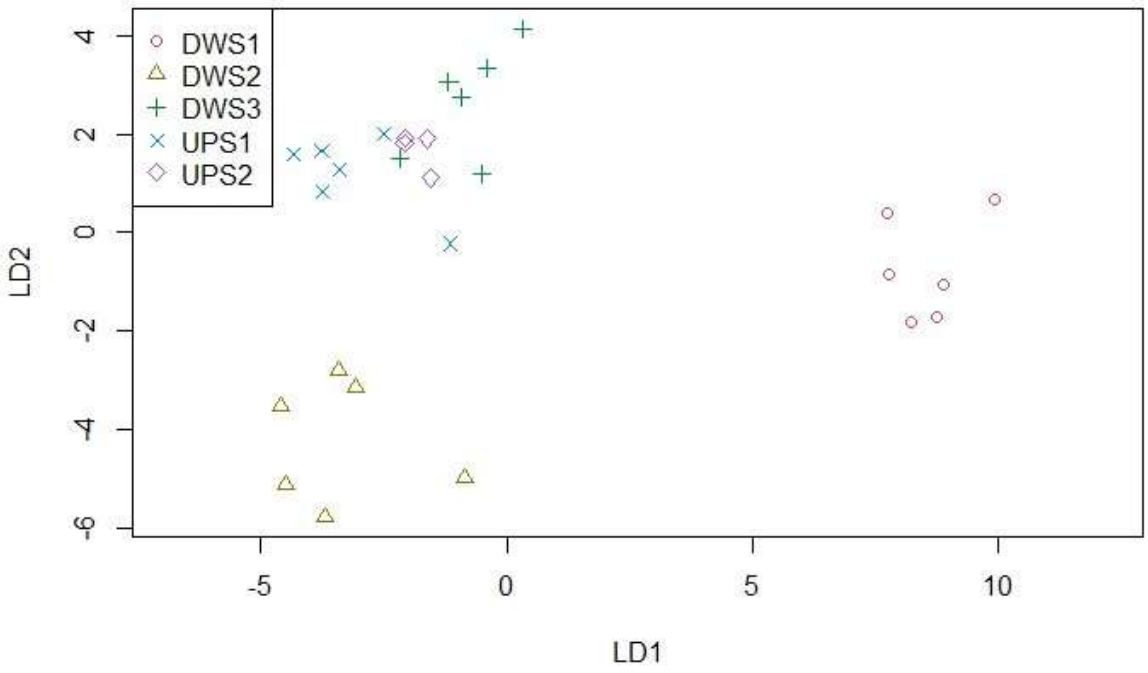


Figure 2. Canonical analysis of principal coordinates plot showing point clusters for the upstream and downstream sampling sites.

Table 5. PERMANOVA results showing statistical differences between the upstream and downstream sites.

	Df	SS	R2	F	Pr(>F)
Site	4	969007.5	0.5848255	8.0996	0.001
Residual	23	687909.7	0.4151745		
Total	27	1656917.2	1		

Table 6. Average site scores for water physicochemical parameters; electrical conductivity (EC), total dissolved solids (TDS), total suspended solids (TSS) sulphate (SO4), dissolved oxygen (DO), temperature (Temp).

Site	pH	EC (µS/cm)	TDS (ppm)	TSS (ppm)	Turbidity (NTU)	SO4 (ppm)	DO (ppm)	Temp (°C)
UPS1	7.41	296.83	197.83	8.07	19.33	17.00	11.22	24.28
DWS1	6.20	580.00	386.83	10.20	10.60	215.18	11.30	24.37
DWS2	7.89	252.22	168.08	12.73	17.58	31.07	11.52	24.37
DWS3	8.63	216.00	143.67	7.20	7.07	15.76	11.55	24.42
UPS2	8.58	214.25	142.75	3.05	4.95	20.15	11.50	26.30

4.2 Aquatic macroinvertebrates

Total scores of the Mini-KASS biomonitoring index range between 78.5 and 93.25 with the lowest score recorded at sampling site DWS1 (Table 7). Mean ASPT scores range between 5.3 to 5.85 (Table 7) falling within the warning range of the Mini-KASS classification of impairment level. Abundancies of the functional feeding groups shows that most of the taxa were predators at all the sampling sites (Fig. 3). Functional feeding groups show variations in correlation in the study area with predators showing a larger correlation with shredders (Fig. 4).

Table 7. Average values of total score, average score per taxon (ASPT) and biotope for each site in the study area

Site	Total Score	ASPT	Biotope
UPS1	83.33	5.30	41.75
DWS1	78.50	5.55	57.42
DWS2	83.67	5.72	17.08
DWS3	82.17	5.60	59.58
UPS2	93.26	5.85	55.88

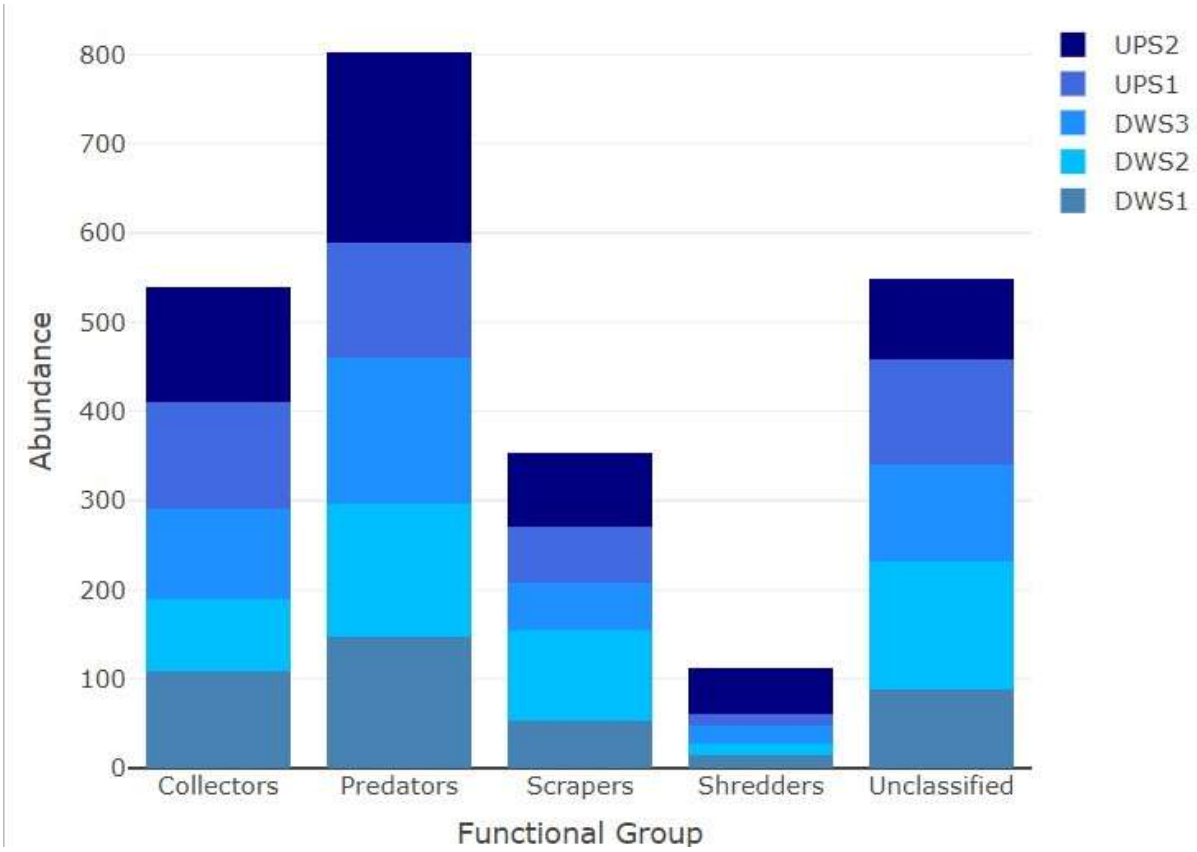


Figure 3. Abundances of macroinvertebrate functional feeding groups (FFG) at each site.

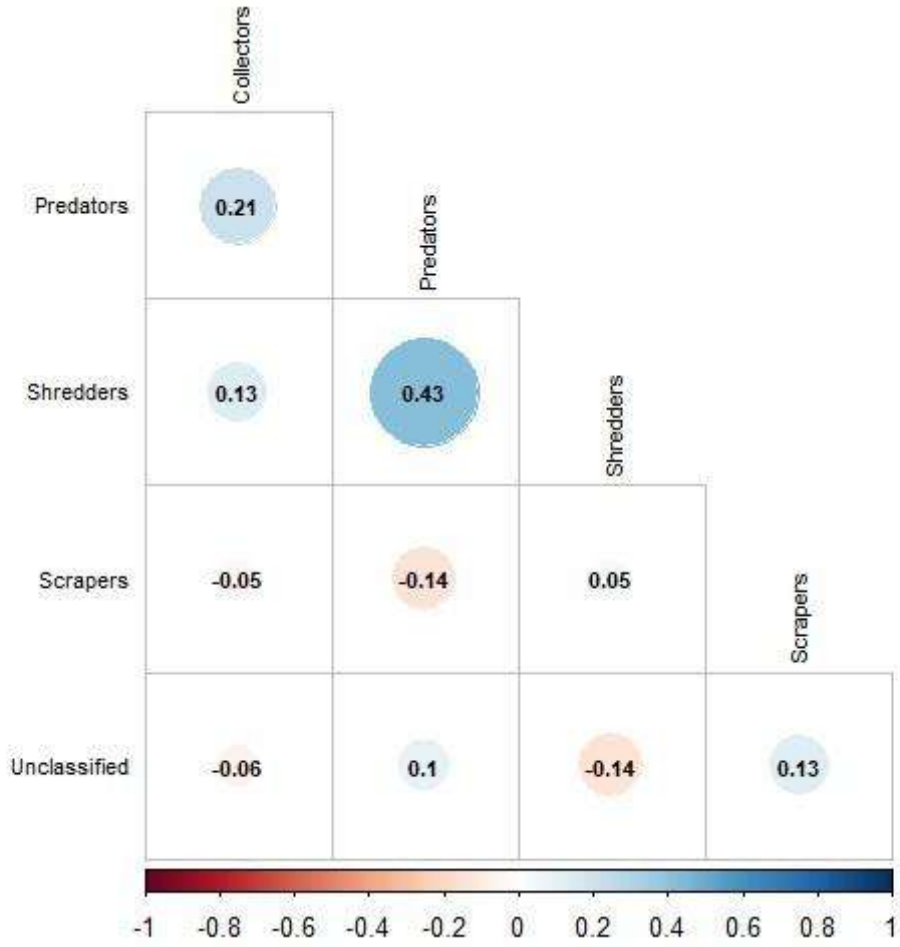


Figure 4. Functional feeding group correlogram for the study area showing the relationships between the four functional feeding groups.

4.2.1 Macroinvertebrates response to physicochemical properties of water

Figures 5 and 6 show the relationships the water parameters and macroinvertebrate metrics. Macroinvertebrate functional feeding group response to water parameters is not preeminent as shown by the canonical correspondence analysis result. However, pH was positively correlated with the macroinvertebrate metrics including total score, number of groups, ASPT, Margaleff diversity index (d) and Simpson's richness index (D). Dissolved oxygen is positively associated with the number of groups and ASPT but shows no correlation with total scores and negative correlations with the other invertebrate metrics. Electrical conductivity, total dissolved solids, and total suspended solids were all negatively correlated with the macroinvertebrate metrics. Turbidity was negatively correlated with the number of groups and the Margaleff richness index, whereas sulphate is negatively correlated with all the invertebrate metrics except ASPT.

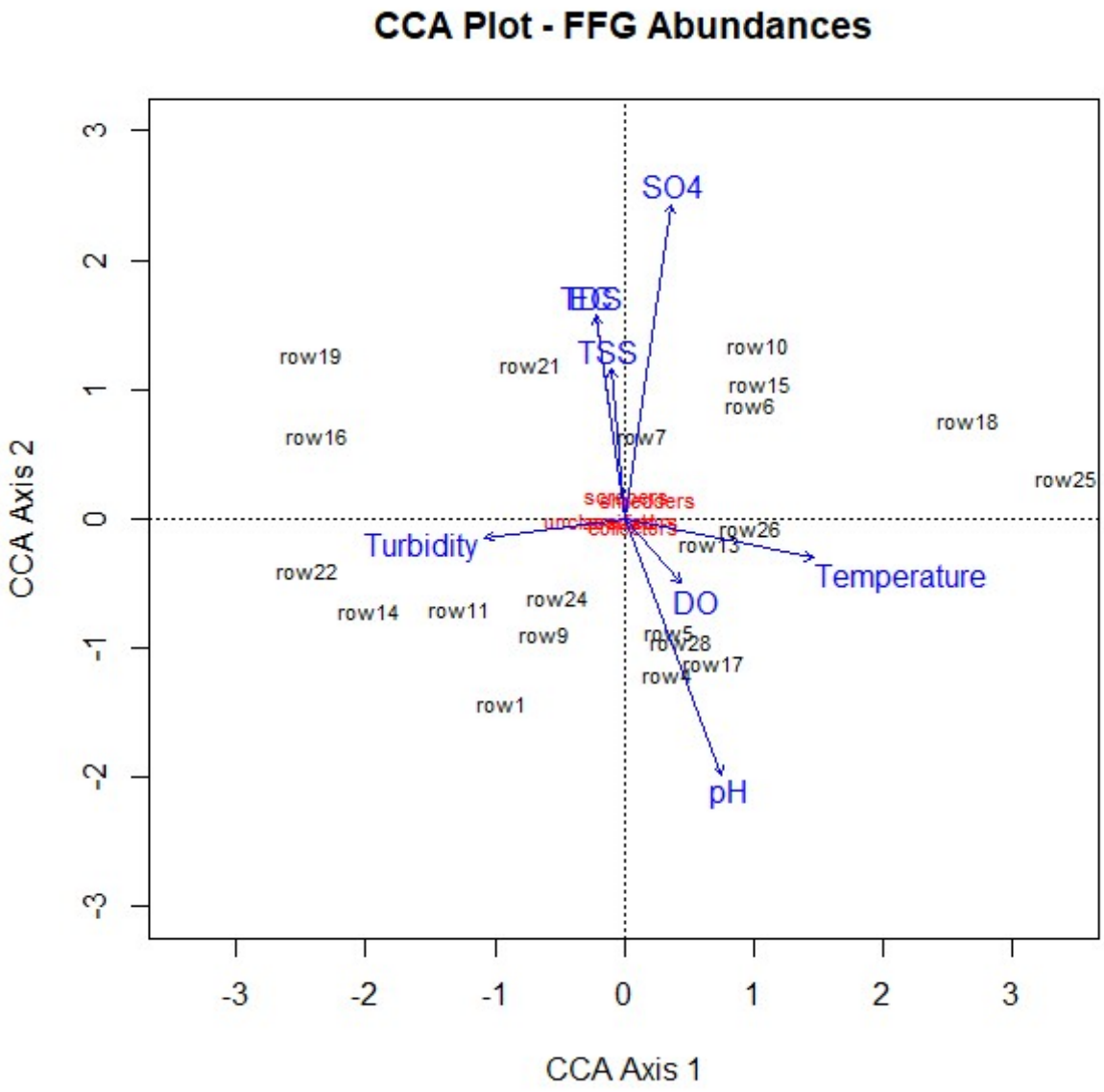


Figure 5. Canonical correspondence analysis of the results between taxonomic groups and water physicochemical parameters. total dissolved solids (TDS), temperature (Temp), dissolved oxygen (DO), sulphate (SO4), total suspended solids (TSS).

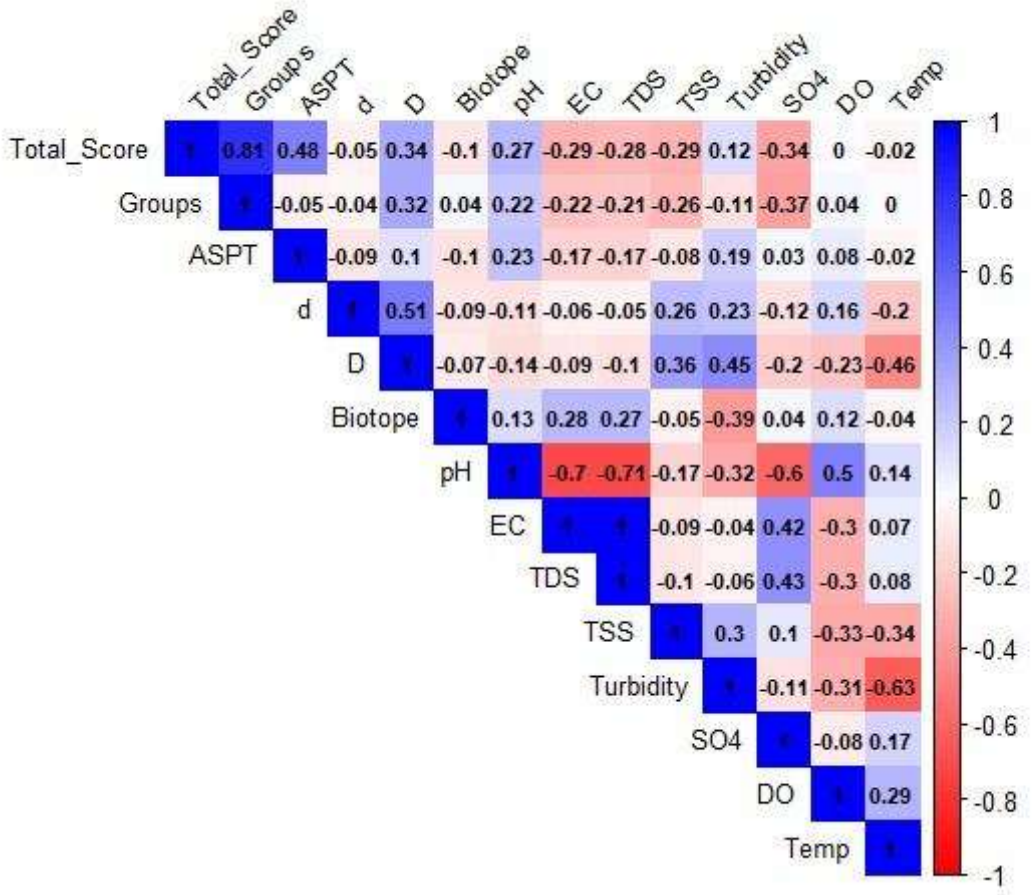


Figure 6. Spearman's correlation between physicochemical parameters of water and macroinvertebrate metrics of total score, number of (taxonomic) groups, average score per taxon (ASPT), Margaleff richness index (d), Simpson's diversity index (D).

4.3 Biotope assessment

Biotope scores for all the sampling sites are presented in Table 7 and Figure 7. The lowest biotope score was recorded at site DWS2 which is mainly dominated by vegetation and sand biotopes (Fig. 7). All other sites have good scores for stones-in-current and stones-out-of-current.

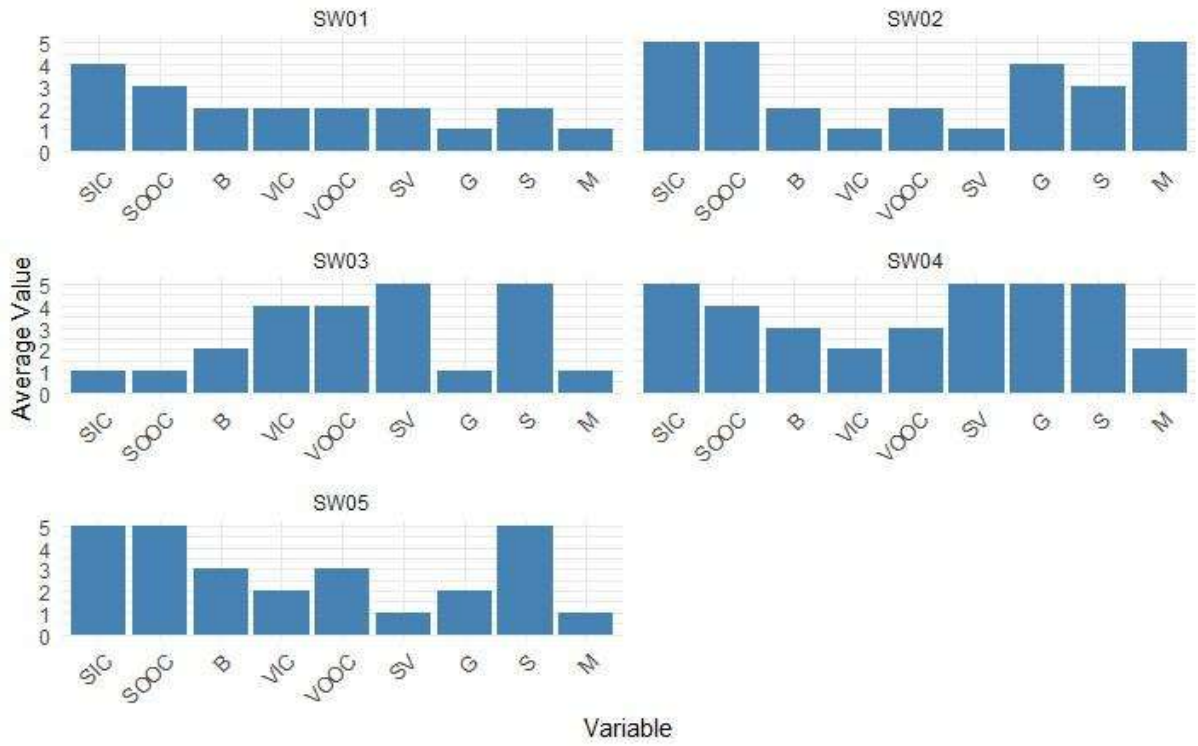


Figure 7. Detailed breakdown of average biotopes at each sampling site. Stones in current (SIC), stones out of current (SOOC), bare rock (B), vegetation in current (VIC), vegetation out of current (VOOC), submerged vegetation (SV), gravel (G), sand (S), mud(M).

4.4 Macroinvertebrates and biotopes

Figure 8 shows the correlations between macroinvertebrate functional feeding groups and biotopes. Strong correlations were not recorded among the variables, but the stone biotopes record positive relations with collectors, predators, and shredders. Scrapers were more strongly positively correlated with vegetation types of biotopes. There were weak or negative relationships between the functional feeding groups and the mud, sand, and gravel biotopes.

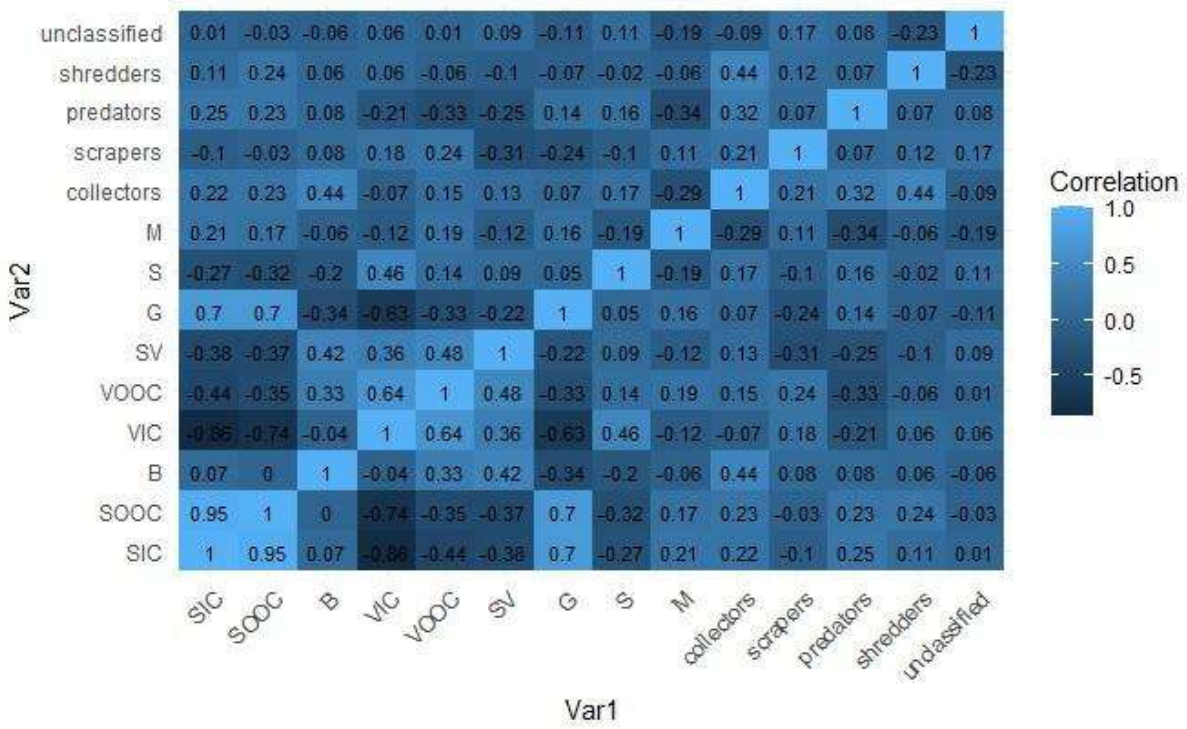


Figure 8. Correlation matrix between macroinvertebrate functional feeding groups and biotopes. Stones in current (SIC), stones out of current (SOOC), bare rock (B), vegetation in current (VIC), vegetation out of current (VOOC), submerged vegetation (SV), gravel (G), sand (S), mud (M).

5. DISCUSSION

5.1 Classification into upstream and downstream sites

In this study, sites that are upstream and downstream of the Nkhachira coal mine were sampled for evaluation of aquatic macroinvertebrates and water parameters (Fig. 1). The CAP result with its associated PERMANOVA underscore a statistically significant difference in the physicochemical parameters between the sites that are upstream and downstream of the mine. The point clustering indicate that physicochemical water parameters play a pivotal role in segregating these site categories and consequently, the selection of these sites as upstream and downstream of the mine was merited.

5.2 Physicochemical parameters and site distinction

The observed variations might possibly be attributed to mining activities particularly in respect of site DWS1 which is closest to the mine and shows elevated sulphate levels (average of 215.18 ppm; Table 6; Appendix II). Mineral leaching, sediment transport and potential mine runoff might contribute to the elevated sulphate levels as well as electrical conductivity and total dissolved solids for the site. Based on the geology of the site and the basic knowledge about acid rock drainage formation, it is possible that sulphide mineral oxidation is beginning to occur within the exposed rock strata and mine waste or stockpile areas. The decreased pH (average of 6.02) at the site might also be indicative of this issue. This needs further investigation since this can be a serious problem for the site and the area. The characteristics of the water

parameters also indicate the possibility of other potential pollution processes or some natural processes that are leading to the variation in these parameters.

5.3 Macroinvertebrate metrics

The ASPT scores were within the warning range of aquatic ecosystem impairment (Table 7) and the functional feeding group abundancies particularly the prevalence of predators (Fig. 3) could reflect a stressed ecosystem. The low minimum abundance of shredders and scrapers can be a good indicator of detrimental human activity impact in the study area (Fig. 3, Mangadze et al. 2019; Bae et al. 2021). This indicates a need for further investigation with more detailed abundance estimates and possibly higher taxonomic level details to establish the true prevalence of different functional feeding groups in the study area. The Mini-KASS index provides a valuable starting point for more detailed investigations. Despite this, the robustness of the index has not been tested which should be a point of consideration for future studies. The sampling time span may have not be sufficient to cover all the morphological stages to adulthood for some of the taxonomic groups. However, the approach is good for a start of such a study in the area and could be supplemented by further data collection in future studies.

5.4 Macroinvertebrates and response to water quality

There are positive and negative associations between macroinvertebrate metrics and water parameters. The positive correlations between macroinvertebrate communities with pH and dissolved oxygen suggest that these parameters create conducive conditions for the invertebrate communities. Conversely, the negative correlations between the macroinvertebrate metrics with sulphates, electrical conductivity, total dissolved solids, and total suspended solids point to the detrimental impacts of these parameters on the macroinvertebrates. Conclusive relationships between macroinvertebrate taxa and water quality parameters could however not be established due to the use of a range of estimated abundancies for the taxa.

5.5 Macroinvertebrates and biotopes

Habitat diversity is important for supporting different macroinvertebrate communities as shown by the connection between biotope scores and macroinvertebrate metrics. Positive correlations between the stone biotopes and some of the functional feeding groups like collectors, predators and shredders show the importance of these habitats to these groups. The weak correlations between the macroinvertebrates and some of the biotopes suggest the likely influence of factors beyond habitat quality on the macroinvertebrate communities. Positive correlations between scrapers and vegetation biotopes as well as negative correlations with the mud, sand, and gravel biotopes could reflect differences in ecological roles played by these biotopes in macroinvertebrate communities around the area. The low biotope score at site DWS2 (Fig. 7) may indicate distinct geomorphological characteristics of this site which is on a river bend (Fig. 1).

6. CONCLUSIONS

The results of this study show that human activities including mining are having an impact on stream ecosystem health around the Nkhachira coal mine. The distinct chemical characteristics at site SW02 including high sulphate levels which can be associated with the available pyrite and the lower pH in comparison to the other sites, point toward mining impact at this site. The

relatively poor stream ecosystem health highlights the need for improved environmental monitoring and management around the site to help mitigate the impacts of human activities on the aquatic ecosystems in the area. It is essential to address both the physicochemical parameters of water as well as biotic aspects in the design of strategies aimed at improving stream ecosystem health in the area. The levels of sulphate near the mine and the decreased level of pH could be indicative of impending water pollution problems in the area. This necessitates follow up studies to look at geochemical characteristics of the area as well as water parameters and macroinvertebrate metrics to follow the changes in stream health in the area.

ACKNOWLEDGEMENTS

I wish to acknowledge the work and efforts of my project supervisor, Dr Jacob Matthew Kasper particularly through his continuous guidance and constructive feedback on my work. My gratitude also goes to the GRÓ LRT staff including Programme Director, Dr. Sjöfn Vilhelmsdóttir, Berglind Orradottir, Halldora Traustadottir, and Brita Berglund for all their support in my studies and practical issues related to my stay in Iceland. I express my thanks to the Lotus Africa and the Department of Mines teams in Malawi for coordinating and supporting my project related activities in Malawi. I want to thank all the instructors during the study programme for helping me enhance my knowledge of ecological restoration and sustainable land management. I express my sincere gratitude to the Government of Iceland through the Ministry of Foreign Affairs and the GRÓ Programme for funding my studies in Iceland. I want to say a big thank you to all the GRÓ LRT fellows of 2023 for their friendship and company during my stay in Iceland. Lasty, I wish to express heartly gratitude to my family for their support during my stay in Iceland.

LITERATURE CITED

Agboola O, Babatunde DE, Isaac Fayomi OS, Sadiku ER, Popoola P, Moropeng L, Yahaya A, Mamudu OA (2020) A review on the impact of mining operation: Monitoring, assessment and management. Results in Engineering 8:100181

Alavaisha E, Lyon S, Lindborg R (2019) Assessment of Water Quality Across Irrigation Schemes: A Case Study of Wetland Agriculture Impacts in Kilombero Valley, Tanzania. Water 11:671

Ali A, Sloane D, Strezov V (2018) Assessment of Impacts of Coal Mining in the Region of Sydney, Australia on the Aquatic Environment Using Macroinvertebrates and Chlorophyll as Indicators. International Journal of Environmental Research and Public Health 15:1556

Bae M-J, Hong J-K, Kim E-J (2021) Evaluation of the Impacts of Abandoned Mining Areas: A Case Study with Benthic Macroinvertebrate Assemblages. International Journal of Environmental Research and Public Health 18:11132

Baker K, Chadwick MA, Kahar R, Sulaiman ZH, Wahab RA (2016) Fluvial biotopes influence macroinvertebrate biodiversity in South-East Asian tropical streams. Ecosphere e01479

Baker K, Chadwick MA, McGill RAR, Wahab RA, Kahar R (2017) Macroinvertebrate trophic structure on waterfalls in Borneo. Marine and Freshwater Research 68:2061

Bergey EA, Ward JV (1989) Upstream-downstream movements of aquatic invertebrates in a Rocky Mountain stream. Hydrobiologia 185:71–82

Bowles D, Morrison L, Dodd H, Rowell G, DeBacker M, Hinsey J, Cribbs J, Haack-Gaynor J, Williams J (2020) Protocol for Monitoring Aquatic Invertebrates at Ozark National Scenic Riverways, Missouri, and Buffalo National River, Arkansas Version 2.0. US Department of the Interior, Colorado. https://www.researchgate.net/publication/339390226_ (accessed 27 June 2023)

Brooks KN, Ffolliott PF, Magner JA (2012) Hydrology and the Management of Watersheds. John Wiley & Sons, Incorporated, Somerset, United States

Business & Human Rights Resource Centre (2018) Malawi: CSOs in mineral-rich Karonga region call for mining framework that respects local community rights, including access to information. https://www.business-humanrights.org/en/latest-news/malawi-csos-in-mineral-rich-karonga-region-call-for-mining-framework-that-respects-local-community-rights-including-access-to-information/ (accessed 3 June 2023)

Carew ME, Pettigrove VJ, Metzeling L, Hoffmann AA (2013) Environmental monitoring using next generation sequencing: rapid identification of macroinvertebrate bioindicator species. Frontiers in zoology 10:45–45

Carter GS, Bennet JD (1973) The Geology and Mineral Resources of Malawi. Malawi Government Printer, Zomba.

Connolly N, Crossland R, Pearson R (2004) Effect of low dissolved oxygen on survival, emergence, and drift of tropical stream macroinvertebrates. 23:251–270

Consolidated Coal Mining Industries Company Limited (2020) Mining Licence Application. Lilongwe, on file with the Commissioner for Mines and Minerals

Cummins KW (2018) Functional Analysis of Stream Macroinvertebrates. In: Gökçe D (ed) Limnology - Some New Aspects of Inland Water Ecology. IntechOpen.

Cummins KW (2021) The Use of Macroinvertebrate Functional Feeding Group Analysis to Evaluate, Monitor and Restore Stream Ecosystem Condition. Reports on Global Health Research. 4:129

Dallas HF (1995) An evaluation of SASS (South African scoring system) as a tool for the rapid bioassessment of water quality. Master's Thesis, University of Cape Town

Dallas HF (2021) Rapid Bioassessment Protocols Using Aquatic Macroinvertebrates in Africa–Considerations for Regional Adaptation of Existing Biotic Indices. Frontiers in Water 3:628227

Dallas HF (2007) The influence of biotope availability on macroinvertebrate assemblages in South African rivers: implications for aquatic bioassessment. Freshwater Biology 52:370–380

Nelson MG(2011) Site Environmental Considerations. pp 1643 - 1664. In: Darling P (ed) SME mining engineering handbook. Society for Mining, Metallurgy, and Exploration, Englewood, Colorado

Dickens CW, Graham PM (2002) The South African Scoring System (SASS) Version 5 Rapid Bioassessment Method for Rivers. African Journal of Aquatic Science 27:1–10

Dolan DM, El-Shaarawi AH (1989) Inferences about Point Source Loadings from Upstream/Downstream River Monitoring Data. pp. 243–257. In: Chapman, DT & El-Shaarawi, AH, (eds) Statistical Methods for the Assessment of Point Source Pollution: Proceedings of a Workshop on Statistical Methods for the Assessment of Point Source Pollution. Springer Netherlands, Dordrecht

Duque G, Gamboa-García DE, Molina A, Cogua P (2022) Influence of water quality on the macroinvertebrate community in a tropical estuary (Buenaventura Bay). Integrated Environmental Assessment and Management 18:796–812

Edegbene AO, Akamagwuna FC, Arimoro FO, Akumabor EC, Kaine EA (2022) Effects of urban-agricultural land-use on Afrotropical macroinvertebrate functional feeding groups in selected rivers in the Niger Delta Region, Nigeria. Hydrobiologia 849:4857–4869

United States Environmental Protection Authority (2011) A Primer on Using Biological Assessments to Support Water Quality Management. Washington DC. https://www.epa.gov/sites/default/files/2018-10/documents/primer-using-biological-assessments.pdf (accessed 3 June 2023)

Food and Agriculture Organisation (2014) World reference base for soil resources 2014. https://www.fao.org/3/i3794en/I3794en.pdf (accessed 16 August 2023)

Girgin S, Kazanci N, Dügel M (2010) Relationship between aquatic insects and heavy metals in an urban stream using multivariate techniques. International Journal of Environmental Science & Technology 7:653–664

Global Reporting Initiative (GRI) (2022) GRI 12: Coal Sector 2022. https://www.globalreporting.org/media/zr3bcrc0/coal_onepager-leaflet.pdf (accessed 23 May 2023)

Hancox PJ (2016) The Coalfields of South-Central Africa: A Current Perspective. Episodes Journal of International Geoscience 39:407–428

Herman MR, Nejadhashemi AP (2015) A review of macroinvertebrate- and fish-based stream health indices. Ecohydrology & Hydrobiology 15:53–67

Hu X, Zuo D, Xu Z, Huang Z, Liu B, Han Y, Bi Y (2022) Response of macroinvertebrate community to water quality factors and aquatic ecosystem health assessment in a typical river in Beijing, China. Environmental Research 212:113474

Hustrulid W, Kuchta M, Martin R (2013) Open Pit Mine Planning and Design. 3rd ed. Taylor & Francis Group, Florida

International Network for Acid Prevention (INAP) (2009) Global Acid Rock Drainage Guide. Global Acid Rock Drainage (GARD) Guide. http://www.gardguide.com/index.php?title=Main_Page (accessed 3 June 2023)

Johnson SW, Drice S, Moles DA (1998) Effects of submarine mine tailings disposal on juvenile yellowfin sole (*pleuronectes aspen*): A laboratory study. Marine Pollution Bulletin 36:278–287

Kamlongera PJ (2013) The mining boom in Malawi: implications for community development. Community Development Journal 48:377–390

Kindt R, Coe R (2005) Tree diversity analysis. A manual and software for common statistical methods for ecological and biodiversity studies. World Agroforestry Centre (ICRAF)

Knight Piesold C (2006) Kayelekera Uranium Project Environmental Impact Assessment Report. Rivonia

Ko NT, Suter P, Conallin J, Rutten M, Bogaard T (2020) Aquatic Macroinvertebrate Community Changes Downstream of the Hydropower Generating Dams in Myanmar-Potential Negative Impacts From Increased Power Generation. Frontiers in Water 2:57

Mangadze T, Wasserman RJ, Froneman PW, Dalu T (2019) Macroinvertebrate functional feeding group alterations in response to habitat degradation of headwater Austral streams. Science of The Total Environment 695:133910

Allgaier FK (1997) Environmental Effects of Mining. pp. 149-153. In: Marcus JJ, (ed.) Mining Environmental Handbook. Imperial College Press, London pp. 132–182.

Margalef R (1958) Information theory in ecology. General Systems, 3, 36-71

Masese F, Kitaka N, Kipkemboi J, Gettel G, Irvine K, McClain M (2014) Macroinvertebrate functional feeding groups in Kenyan highland streams: Evidence for a diverse shredder guild. Freshwater science. 33(2):435-450

Masese FO, Wanderi EW, Nyakeya K, Achieng AO, Fouchy K, McClain ME (2023) Bioassessment of multiple stressors in Afrotropical rivers: Evaluating the performance of a macroinvertebrate-based index of biotic integrity, diversity, and regional biotic indices. Frontiers in Environmental Science 11:1015623

Maus V, Giljum S, Da Silva DM, Gutschlhofer J, Da Rosa RP, Luckeneder S, Gass SLB, Lieber M, McCallum I (2022) An update on global mining land use. Scientific Data 9:433

Muñoz-Mas R, Sánchez-Hernández J, McClain ME, Tamatamah R, Mukama SC, Martínez-Capel F (2019) Investigating the influence of habitat structure and hydraulics on tropical macroinvertebrate communities. Ecohydrology & Hydrobiology 19:339–350

Munyika S, Kongo V, Kimwaga R (2014) River health assessment using macroinvertebrates and water quality parameters: A case of the Orange River in Namibia. Physics and Chemistry of the Earth, Parts A/B/C 76–78:140–148

Nkhoma J (2006) Environmental Impact Assessment Report for Nkhachira Coal Mine. Chiwandama Geoconsultants, Lilongwe

Ogundele LT, Oluwajana OA, Ogunyele AC, Inuyomi SO (2021) Heavy metals, radionuclides activity and mineralogy of soil samples from an artisanal gold mining site in Ile-Ife, Nigeria: implications on human and environmental health. Environmental Earth Sciences 80:202

Oksanen J, Simpson GL, Blanchet FG, Kindt R, Legendre P, Minchin PR, O'Hara RB, Solymos P, Stevens MHH, Szoecs E, Wagner H, Barbour M, Bedward M, Bolker B, Borcard D, Carvalho G, Chirico M, Caceres MD, Durand S, Evangelista HBA, FitzJohn R, Friendly M, Furneaux B, Hannigan G, Hill MO, Lahti L, McGlinn D, Ouellette M-H, Cunha ER, Smith T, Stier A, Braak CJFT, Weedon J (2022) vegan: Community Ecology Package.

Ouma K, Shane A, Syampungani S (2022) Aquatic Ecological Risk of Heavy-Metal Pollution Associated with Degraded Mining Landscapes of the Southern Africa River Basins: A Review. Minerals 12:225

Pence RA, Cianciolo TR, Drover DR, McLaughlin DL, Soucek DJ, Timpano AJ, Zipper CE, Schoenholtz SH (2021) Comparison of benthic macroinvertebrate assessment methods along a salinity gradient in headwater streams. Environmental Monitoring and Assessment 193:765

Phillips JD (2017) Geomorphic and hydraulic unit richness and complexity in a coastal plain river: geomorphic and hydraulic unit richness and complexity. Earth Surface Processes and Landforms 42:2623–2639

Punia A, Singh SK (2021) Contamination of water resources in the mining region. pp. 3–17. In: Ahamad A, Siddiqui SE, Sign P (eds) Contamination of Water. Academic Press.

R Core Team (2022) R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria

Rall K (2016) 'They Destroyed Everything': Mining and Human Rights in Malawi. Human Rights Watch, New York, N.Y.

Raphahlelo ME, Addo-Bediako A, Luus-Powell WJ (2022) Distribution and diversity of benthic macroinvertebrates in the Mohlapitsi River, South Africa. Journal of Freshwater Ecology 37:145–160

Rico-Sánchez AE, Rodríguez-Romero AJ, Sedeño-Díaz JE, López-López E, Sundermann A (2022) Aquatic macroinvertebrate assemblages in rivers influenced by mining activities. Scientific Reports 12:3209

Ritchie H, Rosado P, Roser M (2022) Environmental Impacts of Food Production. Our World in Data. https://ourworldindata.org/environmental-impacts-of-food (accessed 2 June 2023)

Ritchie H, Roser M (2013) Land Use. Our World in Data. https://ourworldindata.org/land-use (accessed 12 June 2023)

Ritchie H, Roser M, Rosado P (2020) CO_2 and Greenhouse Gas Emissions. Our World in Data. https://ourworldindata.org/co2-and-greenhouse-gas-emissions (accessed 2 June 2023)

Rowntree K, Wadeson RA (1999) A Hierarchical Geomorphological Model for the Classification of Selected South African Rivers. Rhodes University, Geography Department. https://www.wrc.org.za/wp-content/uploads/mdocs/497-1-99.pdf

Saini V, Li Jun, Yang Y, Li Jinsong, Wang B, Tan J (2022) Investigating the environmental impacts of coal mining using remote sensing and in situ measurements in Ruqigou Coalfield, China. Environmental Monitoring and Assessment 194:780

Schloerke B, Cook D, Larmarange J, Briatte F, Marbach M, Thoen E, Elberg A, Crowley J (2021) GGally: Extension to 'ggplot2'.

Shakya M, Silvester E, Rees G, Stitz L, Holland A (2021) Spatial variation in the amino acid profile of four macroinvertebrate taxa along a highly polluted river. Environmental Pollution 284:117536

Simpson EH (1949) Measurement of Diversity. Nature 163:688–688

Society for Mining, Metallurgy & Exploration (SME) (2023) Mining and Water Quality. https://www.smenet.org/What-We-Do/Technical-Briefings/Mining-Water-Quality (accessed 3 June 2023)

Spitz K, Trudinger J (2019) Mining and the Environment: from Ore to Metal. 2nd ed. Taylor & Francis Group, London

Staudacher K, Füreder L (2007) Habitat Complexity and Invertebrates in Selected Alpine Springs (Schütt, Carinthia, Austria). International Review of Hydrobiology 92:465–479

Steyn M, Oberholster PJ, Botha AM, Genthe B, Van Den Heever-Kriek PE, Weyers C (2019) Treated acid mine drainage and stream recovery: Downstream impacts on benthic macroinvertebrate communities in relation to multispecies toxicity bioassays. Journal of Environmental Management 235:377–388

Tampo L, Kaboré I, Alhassan EH, Ouéda A, Bawa LM, Djaneye-Boundjou G (2021) Benthic Macroinvertebrates as Ecological Indicators: Their Sensitivity to the Water Quality and Human Disturbances in a Tropical River. Frontiers in Water 3:662765

Texas Commission on Environmental Quality (2014) Surface Water Quality Monitoring Procedures, Volume 2: Methods for Collecting and Analyzing Biological Assemblage and Habitat Data. https://www.tceq.texas.gov/downloads/publications/rg/swqm-procedures-manual-volume-2-rg-416.pdf (accessed 8 August 2023)

The GEOGloWS Initiative (2023) GEOGloWS ECMWF Streamflow Model. https://geoglows.ecmwf.int/ (accessed 23 June 2023)

Timpano AJ, Schoenholtz SH, Soucek DJ, Zipper CE (2018) Benthic macroinvertebrate community response to salinization in headwater streams in Appalachia USA over multiple years. Ecological Indicators 91:645–656

United Nations Environment Programme (UNEP) (2022) Biological monitoring of freshwater environments.https://www.unep.org/technical-highlight/biological-monitoring-freshwater-environments (accessed 3 June 2023)

United States Geological Survey (USGS) (2018) Mining and Water Quality. https://www.usgs.gov/special-topics/water-science-school/science/mining-and-water-quality (accessed 22 June 2023)

Venables WN, Ripley BD (2002) Modern Applied Statistics with S. Fourth. Springer, New York

Wallace JB, Webster JR (1996) The Role of Macroinvertebrates in Stream Ecosystem Function. Annual Review of Entomology 41:115–139

Wei T, Simko V (2021) R package 'corrplot': Visualization of a Correlation Matrix.

Wickham H (2016) ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York

Wickham H, Averick M, Bryan J, Chang W, McGowan LD, François R, Grolemund G, Hayes A, Henry L, Hester J, Kuhn M, Pedersen TL, Miller E, Bache SM, Müller K, Ooms J, Robinson D, Seidel DP, Spinu V, Takahashi K, Vaughan D, Wilke C, Woo K, Yutani H (2019) Welcome to the tidyverse. Journal of Open Source Software 4:1686

Wickham H, François R, Henry L, Müller K, Vaughan D (2023) dplyr: A Grammar of Data Manipulation.

Witchalls S (2022) The Environmental Problems Caused by Mining. https://earth.org/environmental-problems-caused-by-mining/ (accessed 2 June 2023)

Worlanyo AS, Jiangfeng L (2021) Evaluating the environmental and economic impact of mining for post-mined land restoration and land-use: A review. Journal of Environmental Management 279:111623

Hund K, La Porta D, Fabregas TP, Laing T, Drexhage J (2020) Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition. World Bank, Washington DC. https://pubdocs.worldbank.org/en/961711588875536384/Minerals-for-Climate-

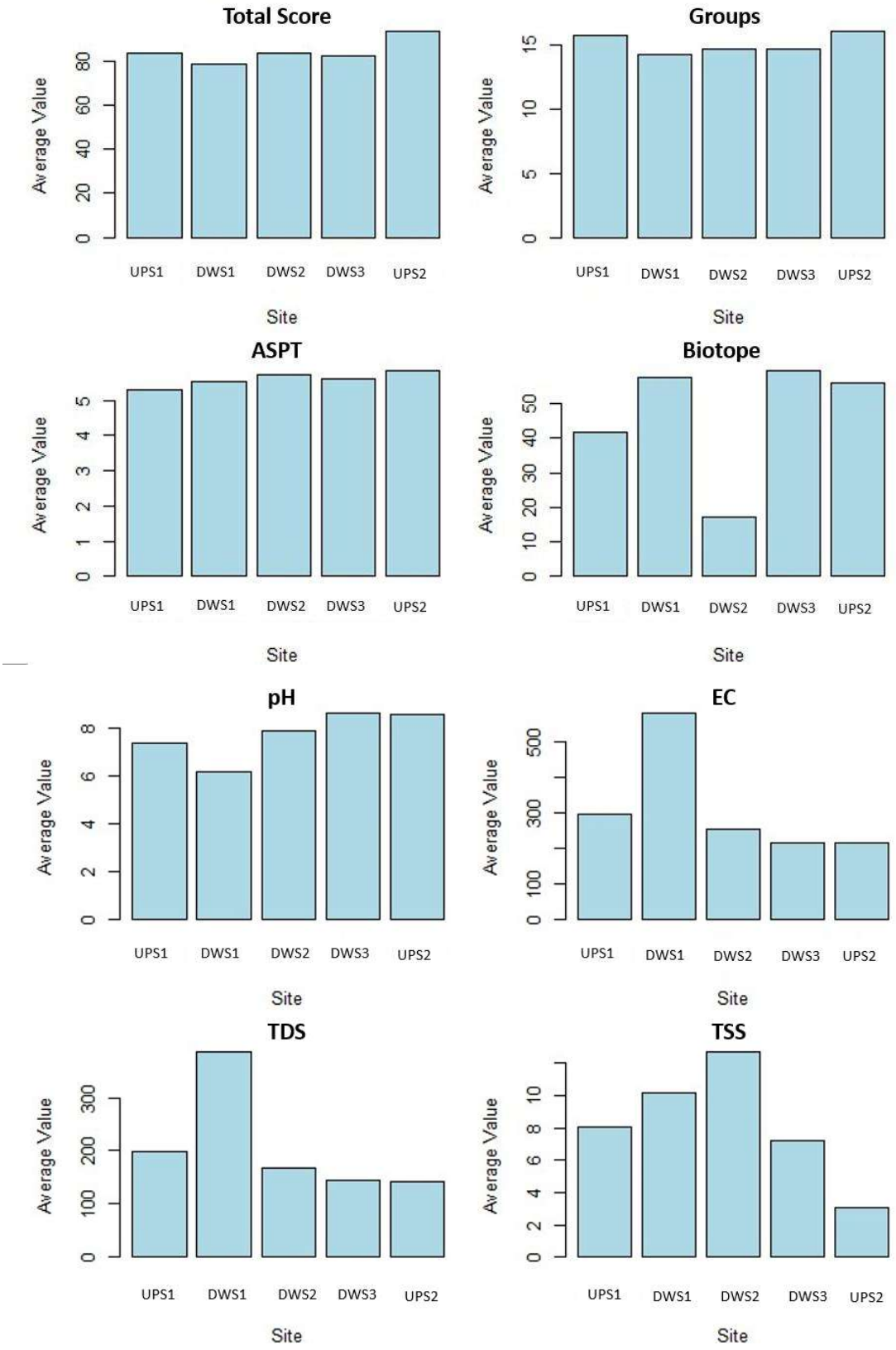
Action-The-Mineral-Intensity-of-the-Clean-Energy-Transition.pdf (accessed 22 June 2023)

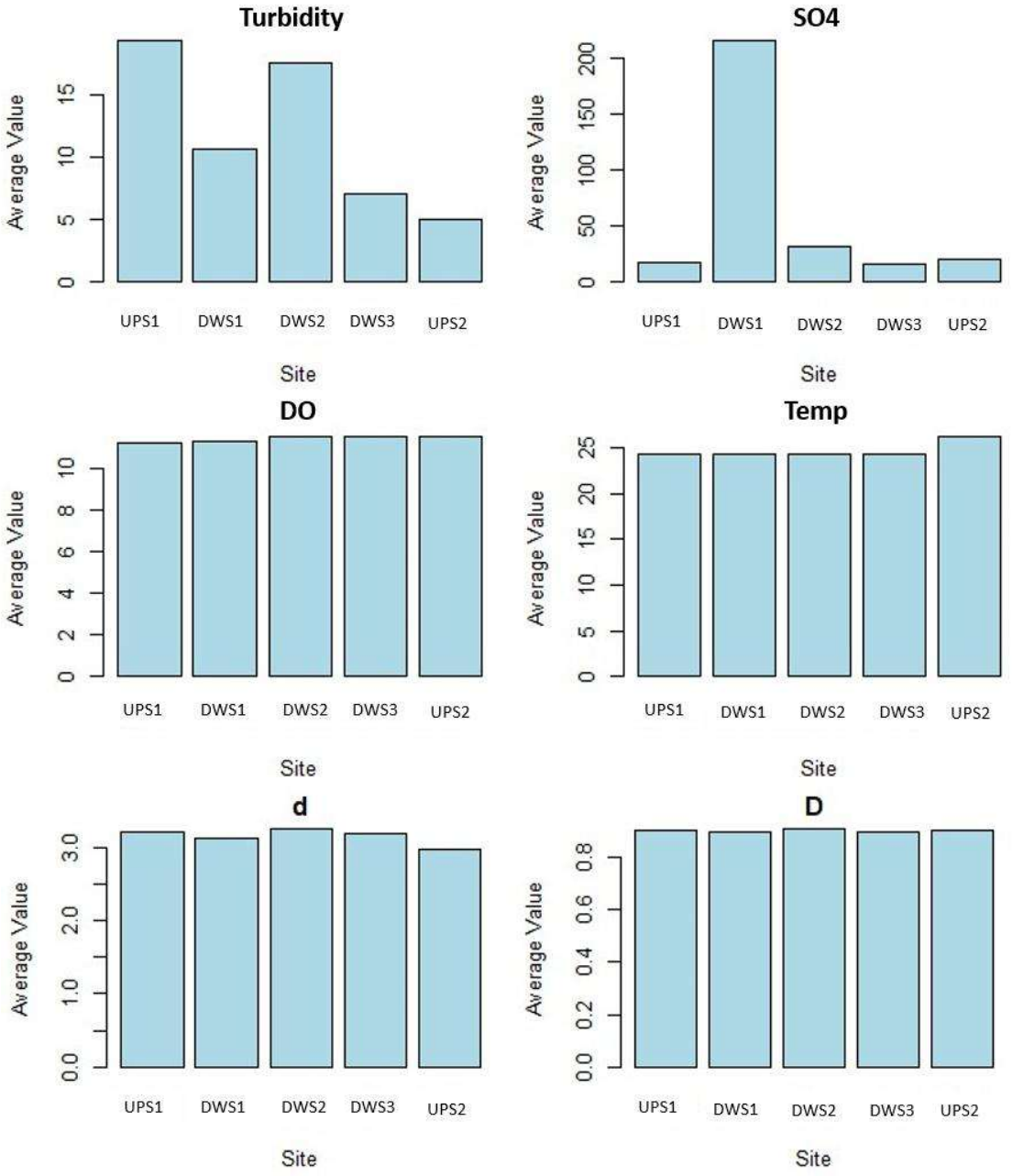
APPENDICES

Appendix I Score Assignment for Taxa in MiniKASS Based on Sensitivity to Water Pollution

Scientific Name	Common Name	Score
Ephemeroptera	Mayflies	
Baetidae	Minnow Mayflies	6
Caenidae	Cainflies	6
Polymitarcyidae	Pale Burrowers	10
Heptageniidae	Flat-headed Mayflies	13
Leptophlebiidae	Prongills	9
	Other mayflies	6
Trichoptera	Caddisflies	
	Caseless	6
	Cased	8
Coleoptera	Beetles	
Psephenidae	Water pennies	10
	Other beetles	8
Hemiptera	Bugs	
Naucoridae	Creeping water bugs	7
Notonectidae	Backswimmers	3
Gerridae	Pondskaters	5
Hydrometridae	Marsh treaders	6
Corixidae	Water boatmen	3
Veliidae	Ripple Bugs	5
Anisoptera	Dragonflies	6
Zygoptera	Damselflies	4
Diptera	Flies	
Culicidae	Mosquitoes	1
Chironomidae	Midges	2
Ceratopogonidae	Biting Midges	5
Tabanidae	Horse flies	5
Simuliidae	Blackflies	5
Tipulidae	Crane flies	5
Plecoptera	Stoneflies	12
Hydracarina	Water mites	8
Potamonautidae	Crabs	3
Oligochaeta	Earthworms	1
Mollusca	Snails	3

Appendix II: Bar plots of average values of the studied parameters




Turbidity
Average Value
0
5
10
15
UPS1
DWS1
DWS2
DWS3
UPS2
Site
SO4
Average Value
0
50
100
150
200
UPS1
DWS1
DWS2
DWS3
UPS2
Site
DO
Average Value
0
2
4
6
8
10
UPS1
DWS1
DWS2
DWS3
UPS2
Site
Temp
Average Value
0
5
10
15
20
25
UPS1
DWS1
DWS2
DWS3
UPS2
Site
d
Average Value
0.0
1.0
2.0
3.0
UPS1
DWS1
DWS2
DWS3
UPS2
Site
D
Average Value
0.0
0.2
0.4
0.6
0.8
UPS1
DWS1
DWS2
DWS3
UPS2
Site

Appendix III: Site pictures

a = UPS1, b = DWS1, c = DWS1, d = DWS3, e = UPS2, f = sampling at UPS1, g = training and field identification of taxa.

