BINDURA UNIVERSITY OF SCIENCE EDUCATION

DEPARTMENT OF ENVIRONMENTAL SCIENCE

The impacts of artisanal mining on groundwater quality around Bindura town.

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A RESEARCH PROJECT SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS OF THE BACHELOR OF SCIENCE (HONOURS) DEGREE IN SAFETY, HEALTH AND ENVIRONMENTAL MANAGEMENT.

Submitted May 2022

Declaration

The undersigned certify that they have read this research project and have approved its submission for marking in relation to the department's guidelines and regulations.

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BINDURA UNIVERSITY OF SCIENCE EDUCATION

26 March 2022

Dear Sir/Madam

REQUEST FOR PERMISSION TO COLLECT DATA FOR ACADEMIC RESEARCH PROJECT

Project Title: The impacts of artisanal mining on groundwater quality around Bindura town.

Academic Supervisor: Mr. P. Nhokovedzo
This letter serves to inform you that **Tinashe Tavanhira Bl92919B** is a 4th year student at Bindura University of Science Education, in the Department of Environmental Science. During her fourth year of study she is supposed to do a research project in her area of specialisation.

Please assist in any possible way. Data collected will be used for academic purposes only and will not be published without your prior consent.

Thank you for your assistance.

Yours faithfully.

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Mr T. Nyamugure

DEPARTMENT OF ENVIRONMENTAL SCIENCE

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Dedication

To my beloved husband Kingdom Badza and my late mom Edline Tavanhira.

Acknowledgements

I would like to thank the Almighty for the valuable gift of life and opportunity to further my studies. Sincere gratitude goes to my family for the support and love. I also thank my project supervisor Mr. P. Nhokovedzo for the guidance and academic criticism towards the success of this dissertation.

Many thanks to Bindura RDC for the permission to undertake the research in their jurisdiction. To the local community and artisanal miners for allowing me to collect groundwater samples *“Makaita basa chose”*.

Special thanks goes to my dearest husband for the financial and emotional support, love and patience. I love you so much *Nzou*.

Abstract

Artisanal and small-scale mining operations is a form of mining which employ basic tools and machinery, and manual labour for mineral ore excavation. It contributes to the Gross Domestic Product of many countries as well as provide a source of livelihood for many people. However, artisanal mining is usually done informally and illegally, characterized by poor technology and hazardous working conditions. Artisanal mining has been reported to cause severe environmental disruptions such as land degradation, pollution, and deforestation, whose impacts are felt long after the mining activities have ceased. As such, the study investigated the effects of artisanal mining on groundwater quality around three mining sites (Chanaka, Kitsiyatota and Makusha) in Bindura. This was necessitated by the mining activities' disposal of toxic substances containing heavy metals with potential to cause detrimental effects if they do not adhere to EMA and WHO permissible limits. The groundwater quality was determined by characterizing pH, BOD, COD, DO and TDS. Also, the groundwater samples were assessed for presence of heavy metals (Cd, Fe, Hg, Pb and Zn). Thus, a complete randomized block design was employed to collect groundwater around the three artisanal mines. The groundwater samples were sourced from boreholes and wells around each mining site and collected in plastic bottles, labelled and tightly sealed. All samples were taken to to the laboratory for analysis using standard procedures. Results showed that, the groundwater had BOD, COD and TDS above the EMA and WHO permissible standards. Kitsiyatota recorded the significantly highest values for BOD (28.7±3.2 mg/L), COD (84.3±7.1 mg/L) and TDS (492.3±32.3 mg/L) respectively. All mining sites had Cd, Fe, Hg, Pb and Zn above EMA and WHO limits. The concentrations of heavy metals in groundwater decreased in the order Makusha > Kitsiyatota > Chanaka. Though the heavy metals were slightly above the set thresholds, continued consumption of the groundwater may lead to clinical effects overtime. From the study findings, it can be recommended that use of ground water from the mining sites for domestic purposes should be done after adequate treatment as it contains heavy metals. As such, artisanal mining sites should treat their effluent before disposal. Future research should focus on ways of reducing groundwater contamination by artisanal miners.

Key words: artisanal mining, EMA limit, groundwater, heavy metals, and WHO limit.

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Accronyms

AAS – Atomic Absorption Spectophotometry
Al – Aluminium
AMD – Acid Mine Drainage
APHA – American Public Health Association
As – Arsenic
ASM – Artisanal and Small-scale Mining
B – Boron
BOD – Biological Oxygen Demand
Ca – Calcium
CBD – Central Business District
Cd – Cadmium
COD – Chemical Oxygen Demand
CRBD – Complete Randomised Block Design
Cu – Copper
DO – Dissolved Oxygen
EC – Electrical Conductivity
EMA – Environmental Management Agency
Fe – Iron
GDP – Gross Domestic Product
Hg – Mercury
ICP-OES – Inductively Coupled Plasma Optical Electro Spectrophotometry
K – Potassium
MANOVA – Multivariate Analysis of Variance
Mn – Manganese
N – Nitrogen
NH_4^+ – Ammonium
Ni – Nickel
NO_3^- – Nitrite
P – Phosphorous
Pb – Lead
PO_4^- – Phosphate
SI – Statutory Instrument
SO_4^- – Sulphate
SPSS – Statistical Package for Social Sciences
TDS – Total Dissolved Solutes
TSS – Total Suspended Solids
WHO – World Health Organisation
Zn – Zinc

Chapter One: Introduction

1.1 Background to the Study

Artisanal and small-scale mining (ASM) refers to mining operations which employ basic tools and machinery, and manual labour for mineral ore excavation (Canavesio, 2014). It contributes to the Gross Domestic Product (GDP) of many countries producing approximately 10% of global mined gold (World Bank, 2013) and providing a source of livelihood for many people. Ghana small scale mining of gold and diamond provides employment for thousands of people contributing 34.3% of the country's total gold output (Ntibrey, 2016). In Zimbabwe, 25% of the total gold production is contributed by small-scale gold miners (Mujere and Isidro, 2016). Although artisanal mining contribute to the GDP of the country, the impact of their activities threaten the concept of sustainability particulary freshwater which is scarce.

Artisanal mining is usually informal and mostly done illegally (Adebayo *et al.*, 2017) and characterized by poor technology, low productivity and hazardous working conditions (Emel *et al.*, 2011). ASM has been reported to cause severe environmental disruptions (Mujere and Isidro, 2016) such as land degradation, pollution, and deforestation (Ojulari, 2021). Contamination of the environment occurs as a result of heavy metals. These heavy metals are non-biodegradable and persist in the environment affecting soil attributes such as cation exchange capacity, bulk density, nutrients and pH (Khan *et al.,* 2012). When soil quality is affected, plant quality also deteriorates due to extraction of contaminants from soil via the roots. Similarly, ground water is contaminated by leaching and seepage of toxic substances from ASM activities (Ojulari, 2021). Overtime, pollution of both ground and surface waters deprive communities access to water, which is a basic need for human survival. The impacts of ASM are felt long after the mining activities have ceased (Macdonald *et al.*, 2016). This is a result of the haphazard nature of the operations and the use of toxic substances such as cyanide and mercury in gold recovery (Zagury *et al.*, 2014).

Some healthy impacts of drinking contaminated water due to pollution from artisanal mining include lung and kidney dysfunction, bone defects, high blood pressure, suppressing the immune system, cancer, damage to the reproductive and nervous system and causing anaemia and anorexia (Pratush *et al.*, 2018; Gabriel *et al.*, 2019). In addition, water pollution results in poor or inadequate supply which might lead to poor sanitation and hygiene or force residents to acquire water from alternative sources which might be contaminated (Craun *et al.,* 2010; Chigor *et al.,* 2013). Consumption of unsafe drinking water will lead to the outbreak of diarrheal diseases like cholera, dysentery and typhoid (WHO, 2017) as well as health risks from other environmental components e.g., arsenic (As), cadmium (Cd) and mercury (Hg) (Pratush *et al.,* 2018; Gabriel *et al.,* 2019). Excessive ingestion of these trace elements through contaminated drinking water may result in cancer, memory lapses, kidney failure, anaemia and damage to the reproductive system (Edokpayi *et al.,* 2018).

Of great concern is the quality of water utilised by households which should conform to quality standards as it affects human health especially if it is acquired from unsafe sources (WHO, 2017). Unsafe water may be contaminated by microbes, chemicals and trace elements hence, determination of water quality might aid in preventing potential health risks that could emanate from consumption of unsafe water (Daud *et al.,* 2017). Some of the important water quality parameters include biological oxygen demand (BOD), chemical oxygen demand (COD), dissolved oxygen (DO), nitrates, pH, phosphates, total dissolved solids (TDS) and trace elements (APHA, 2012; WHO, 2017).

Considering that artisanal mining operations are undertaken on a daily basis in the study area, and continue to deteriorate environmental quality, it is therefore imperative to investigate the impacts of ASM on groundwater quality.

1.2 Problem Statement

There is a lack of knowledge on the quality of groundwater around artisanal mining sites surrounding Bindura town i.e., Chanaka, Kitsiyatota and Makusha. Previous studies on water quality in Bindura e.g., Hoko, (2008) focused on water quality for borehole rehabilitation. This is because artisanal mining is done consistently throughout the year in a haphazard manner, and the chemicals used contaminate the soil and reach ground water through leaching. Ultimately this may result in detrimental effects to communities around these sites considering that groundwater is their only source of potable water. Contamination of the aquifer does not only threaten the quality of human health but also poses a risk to sustainable development and management of groundwater resources.

1.3 Significance of the Study

The study will provide baseline data for future researches on the status of groundwater around artisanal mining sites as well as raise awareness on the effects of artisanal mining on ground water quality. In addition, the findings will aid artisanal miners to be environmentally conscious and encompass sustainability in their mining practices, as well as enable proper waste management. Furthermore, it will assist local authorities in formulating policies on the conservation of groundwater and provide a basis for corrective action. If not analysed, the contaminated ground water has the potential to cause health risks to residents around these sites if continually consumed (Pratush *et al.*, 2018; Gabriel *et al.*, 2019). Thus, the study will hasten the authorities to provide piped water to these affected areas. It is therefore imperative to quantify the heavy metal concentrations in the ground water emanating from artisanal mining activities and determine if they conform to permissible levels as per EMA and WHO regulatory standards (Edokpayi *et al.* 2018; Mujere and Isidiro, 2016). In addition, this will promote the United Nations‘ Millennium Development Goal 7c of providing access to safe drinking water and basic sanitation (Satterthwaithe, 2016; Well, 2014; Westrate *et al.* 2019; UN, 2017).

1.4 Study Aim

To investigate the impacts of artisanal gold mining on groundwater quality.

1.5 Study Objectives

i. To determine groundwater quality parameters (BOD, COD, DO, pH and TDS) around three artisanal mining sites.
ii. To determine the concentration of trace elements in groundwater around artisanal mining sites.
iii. To compare groundwater quality parameters with EMA and WHO standards.

1.6 Study Hypotheses

i. There is no significant difference in groundwater parameters around the artisanal mining sites.
ii. Concentrations of trace elements in groundwater are significantly different around the mining sites.
iii. Groundwater quality parameters are significantly different with EMA and WHO standards.

Chapter Two: Literature Review

2.0 Introduction

This chapter explores relevant literature on ASM. A brief account of the impacts of mining on groundwater and the effects of heavy metals is presented.

2.1 Artisanal and Small-Scale Mining

Artisanal mining refers to small scale informal mining activities with low technology or minimal machinery involved (Hentschel *et al.,* 2003) with a lot of people involved in artisanal mining compared to those working in industrial operations (World Bank, 2009). Artisanal gold mining plays an important role in global gold production and contributes to the GDP of many countries. However, artisanal mining utilizes the mercury (Hg) amalgamation technique (Feng *et al.,* 2006) that unfortunately leads Hg contamination due to its low recovery during the mining process (Velasquez-Lopez *et al.,* 2010). Another chemical used in gold recovery is cyanide which binds readily with gold, silver and metals, making it a viable chemical for gold extraction (Zagury *et al.,* 2014). Cyanide is highly toxic to human, plant and animal life (Kyoseya *et al.*, 2009). After the gold has been extracted from the ore, the Hg or cyanide and heavy metal-laden wastewater is discharged as process effluent into the tailings pond.

Tailings are a mixture of crushed rock and processing fluids from mills, concentrators that remain after mineral extraction from an ore resource (Densmore *et al.,* 2014). Tailings are characterised by heavy metals such as Cd, Pb, Cu, Ni, and Zn, low fertility, bareness and dust emissions (Pratush *et al.*, 2018). There is limited vegetation establishment on mine tailings (Kossof *et al.*, 2018). Due to the nature of artisanal mining activities, the tailings facilities are usually poorly designed, constructed and monitored, and contain large quantities of heavy metals (Alloway, 2013). Poisonous substances in the oxide and sulphide forms of these aforementioned metals may be released into terrestrial environments through weathering processes and pose a potential health risk to residents in the vicinity of mining operations (Alloway, 2013).

2.2 Water quality parameters

The important water quality parameters include biological oxygen demand (BOD), chemical oxygen demand (COD), dissolved oxygen (DO), nitrates, pH, phosphates, total dissolved solids (TDS) and trace elements (APHA, 2012; WHO, 2017). The BOD is the amount of DO that is required to breakdown organic matter by aerobic biological organisms in water for a given period under specific temperature (Gu *et al.,* 2013), whereas the COD is defined as the oxygen required for the biological decomposition of organic matter and dissolved solids in water by microorganisms under standard temperature (Abba and Elkiran 2017). These parameters are indicators of pollution in ground and surface water (Jain and Kumar, 2014; Abba and Elkiran, 2017). Very high BOD and COD means the oxidation of organic compounds in water is high and as such will reduce DO content (Jain and Kumar, 2014).

The DO is an indicator of a water body's condition for production and the DO concentration decrease with increasing temperature and dissolved solids as well as the presence of oxidisable organic matter from waste discharges (APHA, 2012). TDS represent the concentration of particulate matter in solution in wastewater in the form of colloids (Rhoades, 1996). Another significant water parameter is pH which is a measure of acidity or alkalinity of the water and affects nutrient availability (APHA, 2012). Low pH (< 3) leads to a reduction in macronutrients i.e., K, N and P whereas high pH (>11) results in a reduction of micronutrients e.g., B and Ca (Abba and Elkiran, 2017). Trace elements are poorly soluble in water, cannot be degraded and tend to accumulate overtime. Due to their toxicity, persistence and subsequent bio-accumulation they may lead to detrimental health effects (Gabriel *et al.,* 2019).

2.3 Impacts of Mining on Water

The intense mineral extraction in mining areas has produced a large amount of waste rock and tailings (Mabhena, 2012). Without proper management, the abandoned waste rock and tailings containing heavy metals which are non-degradable, persistent and irreversible thus generating highly pollutant acid mine drainage (AMD) (Besseah, 2011). This affects both soil and groundwater quality. Acid mine drainage predominantly caused pyrite weathering dissolve to produce very acidic waters (pH < 3), which are soluble to heavy metals and other toxic elements and cause them to be transported into groundwater through percolation (Acheampong *et al.,* 2013). When discharged or leached from waste rock and tailings into rivers, heavy metals become a part of water-sediment equilibrium and could be strongly accumulated in sediments (Bo *et al.,* 2018). The continuous adsorption-desorption process between sediments and water prolong the residence time of heavy metals thus they end up further reaching groundwater via seepage.

Due to the dredging activities and the washing of alluvial gold in the water, siltation is common in major rivers and streams where the miners operate resulting in water courses of streams and rivers being altered or diverted (Bansah *et al.,* 2016). During ore processing, Hg is used and constitutes the major pollutants of surface and ground water in small scale gold mining areas (Ntengwe, 2006). Mercury is very volatile and only slightly soluble in water. It is dispersed very effectively through the atmosphere with long residence time in the environment (Velasquez-Lopez *et al.,* 2010). Also, due to its protein binding properties, it readily bio-accumulates and bio-magnifies in along the food chain. As such it is a potent neurotoxin that damages the central nervous system.

Mine wastewater from different mining activities has been reported to be laden with heavy metals, for example, Acheampong *et al.,* (2013) reported that most parameters measured for tailings wastewater such as DO, EC, TDS, PO_4^{3-} and SO_4^{2-} exceeded the permissible limit set by the Ghana EPA and the WHO guideline values with As, Fe and cyanide as the most toxic constituents. It was concluded that the wastewater could not be discharged into the environment without prior treatment. Likewise, Boamponsem *et al.,* (2012) showed that the concentration of Cd, Fe, Mn, Pb and Zn in the wastewater for irrigation were above the WHO permissible limits with the exception of Cu.

In another study by Acheampong *et al.,* (2013), results showed extremely high values for turbidity and TSS in the process effluent due to the presence of high amounts of crushed rock and earth material from which the gold was extracted. However, the tailings dam wastewater had lower TSS and turbidity values due to TSS settling in the tailings pond. Also, the COD (1.24mgL) values were higher than the permissible limits though the BOD (< 50mgL) and DO (< 5mgL) values were within the WHO (2008) acceptable limits. On the other hand, Acheampong *et al.,* (2013) reported that NO^{3-} was the only inorganic compound below the accepted guidelines amongst other compounds that were analysed (NH^{4+}, NO^{3-}, PO_4^{3-} and SO_4^{2-}). Thus, it was concluded that the wastewater should not be discharged without prior treatment into the environment.

Seepage of oils and fuels containing hydrocarbons reach ground water through infiltration with detrimental effects to the groundwater (Ma *et al.,* 2015). In addition, improper solid waste disposal and waste generated from cleaning and maintenance of mining machinery and vehicles can contact groundwater thus affecting its quality (Xiao *et al.,* 2017). Likewise, Ahialey *et al.,* (2010) reported that groundwater contained significant concentrations of Al, Cd and Fe above WHO limits for drinking water in the Pra basin of Ghana. In addition, artisanal mining was recognized as the primary source of heavy metals in the surrounding environment of the basin.

2.4 Effects of Heavy Metals on Human Health

Heavy metals have varied adverse effects to plants, animals and humans at different concentrations leading to declines in growth and reproduction of organisms and in some cases death (Pratush *et al*., 2018; Gabriel *et al*., 2019). Table 2.1 shows the impacts of some selected heavy metals.

Table 2.1. Adverse effects of selected heavy metals on human health

Heavy metal	Adverse effects in humans
Cd	Cause lung and kidney dysfunction, bone defects, high blood pressure and suppresses the immune system
Fe	Causes cancer
Hg	Causes brain damage, dermatitis, protoplasm poisoning, kidney failure, corrosive to skin, eyes and muscles
Pb	Damages kidneys, joints and reproductive and nervous system, anemia, anorexia, loss of appetite, high blood pressure and malaise
Zn	Carcinogenic

2.5 Regulation of Mine Effluent

EMA Effluent and solids waste disposal regulation SI 6 of 2007 regulates the discharge and disposal of solid waste. Discharge of effluent is regulated by this standard whereby they apply the polluter pays principle when mines acquire licenses so that they can discharge effluent into rivers. The regulation has quality standards that stipulate the maximum permissible concentration of pollutants in effluent to be discharged (EMA, SI 6 of 2007). The permissible limits are divided into colour classes (blue, green, yellow and red) depending on the level of risk associated with the discharge. The colour Blue denotes that the effluent is environmentally safe, Green symbolizes low environmental hazard, Yellow represents moderate environmental hazard and Red means high environmental hazard. There are also some international standards such as WHO guidelines that regulate the concentrations of pollutants in soil, water and plants emanating from activities like mining (WHO, 2017).

Chapter Three: Research Methodology

3.0 Introduction

This chapter describes the study area as well as describing the materials, tools and methods used to collect the study data. The statistical analysis procedures are also explained.

3.1 Description of Study Area

3.1.1 Location

The study was carried out in artisanal mining sites surrounding Bindura town (17°18’32.92”S and 31°19’57.45”E) (Figure 3.1) namely Chanaka (17°16’43.08”S and 31°21’1.83”E) which is 5km North East from the town’s CBD along Mt Darwin road, Kitsiyatota (17°18’48.44”S and 31°19’7.46”E) situated 1km West from the CBD and Makusha (17°18’2.20”S and 31°19’32.57”E) approximately 3km East of the CBD along Shamva road. The town is a small mining and agricultural community situated approximately 88km due North East of Harare and is easily accessed by road and rail. The study sites are within mining claims, the bulk of which are artisanal and illegal miners.

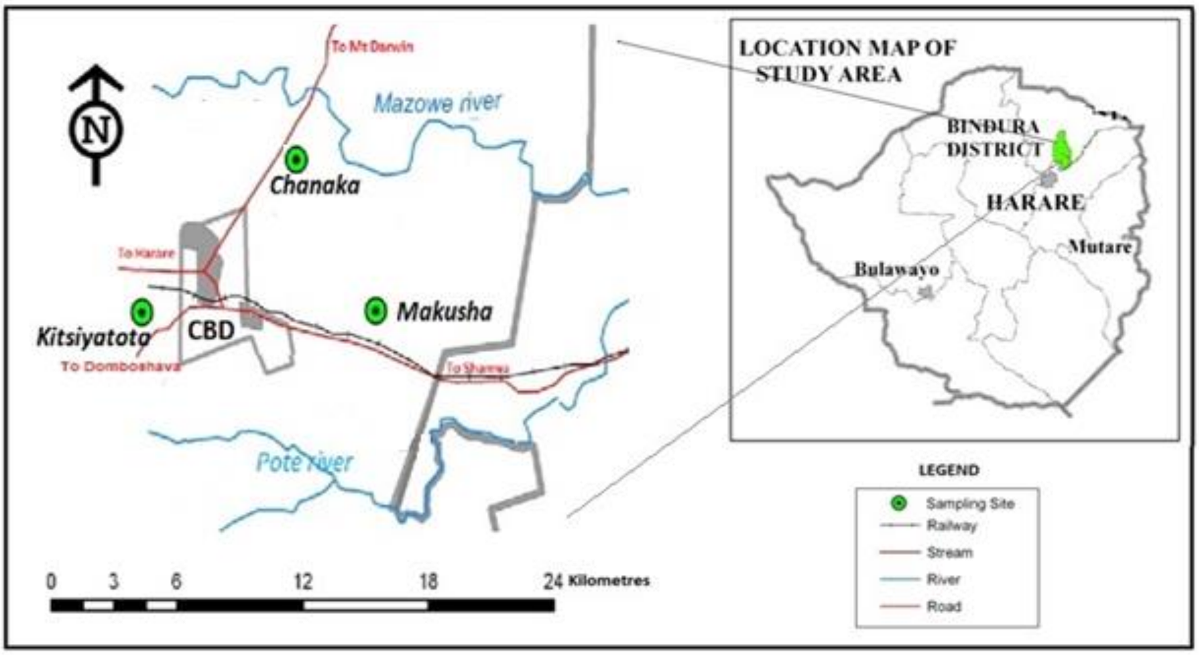

Fig. 3.1: Map showing location of study area

3.1.2 Climate

The sites are situated in Zimbabwe’s Agro-ecological region IIb that is characterised by distinct wet and dry seasons (Mugandani *et al.*, 2012). The annual precipitation ranges from

750mm to 1000mm mostly occurring from December to March. The average temperature is 26°C with the hottest months being October and November whereas May and June are the coldest months (Mugandani *et al.,* 2012).

3.1.3 Vegetation

The study sites are located in a miombo woodland that is dominated by *Brachystegia boehmii, B. spiciformis Julbernardia globiflora.* Other associated woody species include *Acacia polyacantha, Bauhinia petersiana, Diplorhynchus condylocarpon* and *Pilliostigma thoningii.* The area is also situated in a Hyparrhernia grassland dominated by *Hyparrhenia filipendula* in association with *Bothriochloa radicans, Cynodon dactylon, Heteropogon contortus, Melinis repens, Penisetum setaceum, Pogonathria squarrosa, Sehima galpini* and *Setaria sphacelata*.

3.1.4 Geology and Soils

The geology of the study area belongs to the Zimbabwe Craton in the Harare-Shamva Greenstone belt wedged between the Chinamora, Murehwa and Madziwa batholiths. The schist belt commences around Harare with an East-West trend and swings north to the mining village of Mazowe on the western end. Therefore, the schist belt swings to the East through the gold mining towns of Bindura and Shamva. Part of the Bindura greenstone belt splays towards the North to form the Mt Darwin-Umfurudzi-Makaha linear belt. Metamorphic mineral assemblage indicates green schist faces to upper amphibolite faces range of metamorphic grades across the belt. On the other hand, Chanaka site is composed of shallow sandy soils of the fersiallitic group that are grey in colour whereas the Kitsiyatota and Makusha sites have deep well drained red loam soils of the vertisol group with distinct horizons below a topsoil that is rich in organic matter.

3.2 Experimental Design

The study employed a complete randomized block design (CRBD) with each artisanal mining site (Chanaka, Kitsiyatota and Makusha) as a block for the collection of soil samples.

3.3 Groundwater Samples Collection and Analysis

Water samples were collected in triplicates from boreholes and wells within each study site whereas a borehole in Chipadze high density residential area away from mining activities was used as a control. The ground water samples were collected using standard procedures (APHA, 2012) in 2 litre plastic containers, properly labelled, sealed and taken to Trojan

Nickel Mine Waterworks Laboratory for subsequent property analysis. Sampling points were selected such that the samples taken were representative of the water source.

At the laboratory, water samples were taken in standard quantities for the determination of physicochemical parameters using standard procedures (Table 3.1) and also heavy metals (Cd, Fe, Hg, Pb and Zn) accumulation using Atomic Absorption Spectrophotometry (AAS) and Inductive Coupled Plasma Optical Electro Spectrophotometry (ICP-OES) (Spectro-Arcos, model iCAP 6000 SERIES) as described by Esterfern *et al.,* (2013).

Table 3.1: Standard soil sample analysis procedures

Parameter	Method	Parameter	Method
pH	$CaCl_2$ of water and pH meter	DO	Titration
BOD	Titration	TDS	Electrical Conductivity meter
COD	Titration	Trace elements	AAS

3.4 Quality Control Procedures

Safety measures, use of appropriate apparatus and standard operating procedures was exercised to exclude error and ensure reliability of the results. Samples were kept sealed and handled carefully and separately whilst following good laboratory practices to avoid cross-contamination. All the apparatus were rinsed with deionised water after every use, and all analytical procedures were done in triplicates to ensure validity.

3.5 Statistical Analyses

The Statistical Package for Social Sciences (SPSS) software version 22.0 was used to sort and analyse data. Data were analysed for normality and a multivariate analysis of variance (MANOVA) at $p < 0.05$ level of significance) was used to test for significant differences of measured parameters across the study sites.

Chapter Four: Results

4.1 Water Quality Parameters

Table 4.1 shows the characteristics of ground water around artisanal mines surrounding Bindura town in comparison with EMA and WHO guidelines. Results show that the ground water around the three artisanal mining sites were not significantly different in BOD, DO and TDS concentrations ($p > 0.05$). The pH for Makusha was significantly different from other mining sites ($p < 0.05$). Similarly, the COD for Kitsiyatota was also significantly different from other mining sites ($p < 0.05$). In addition, the BOD, COD and TDS were above the EMA and WHO limits, whereas the DO content was below the required threshold by both EMA and WHO for all artisanal mining sites. Chanaka was the only site that recorded a pH value outside the required guideline by EMA and WHO, and had the lowest DO (33.3±0.4 mg/L). Kitsiyatota recorded the significantly highest values for BOD (28.7±3.2 mg/L), COD (84.3±7.1 mg/L) and TDS (492.3±32.3 mg/L) respectively.

Table 4.1: Comparison of ground water quality around three artisanal mines with EMA and WHO guidelines

Sampling site	pH	BOD (mg/L)	COD (mg/L)	DO (%)	TDS (mg/L)
Chanaka	5.9 ± 0.5^{a}	27.2 ± 8.3^{a}	79.6 ± 3.4^{a}	33.3 ± 0.4^{a}	454.1 ± 24.8^{a}
Kitsiyatota	6.4 ± 0.3^{a}	28.7 ± 3.2^{a}	84.3 ± 7.1^{b}	35.1 ± 0.9^{a}	492.3 ± 32.3^{a}
Makusha	7.0 ± 0.8^{b}	26.2 ± 5.1^{a}	78.2 ± 6.2^{a}	37.4 ± 0.3^{a}	488.0 ± 54.1^{a}
Control	7.6 ± 0.2^{b}	13.2 ± 1.9^{b}	22.7 ± 4.9^{c}	83.3 ± 0.7^{b}	177.5 ± 19.6^{b}
EMA limit	6-8	< 15	< 30	> 75	< 100
WHO guideline	6.5-8.5	< 20	< 50	> 40	< 450

Different superscripts a, b, c down a given column indicate significantly different ($p < 0.05$).

4.2 Trace Element Concentrations in Groundwater

The concentrations of heavy metals in ground water are depicted in Fig. 4.1 to 4.5. All mining sites were significantly different in Cd concentrations ($p < 0.05$) with Kitsiyatota recording the significantly highest Cd (0.45±0.02 mg/L) concentrations. The Cd concentrations declined in the order Kitsiyatota > Makusha > Chanaka > Control. In addition, the Cd concentrations for all mining sites was above the EMA and WHO limits (Fig. 4.1).

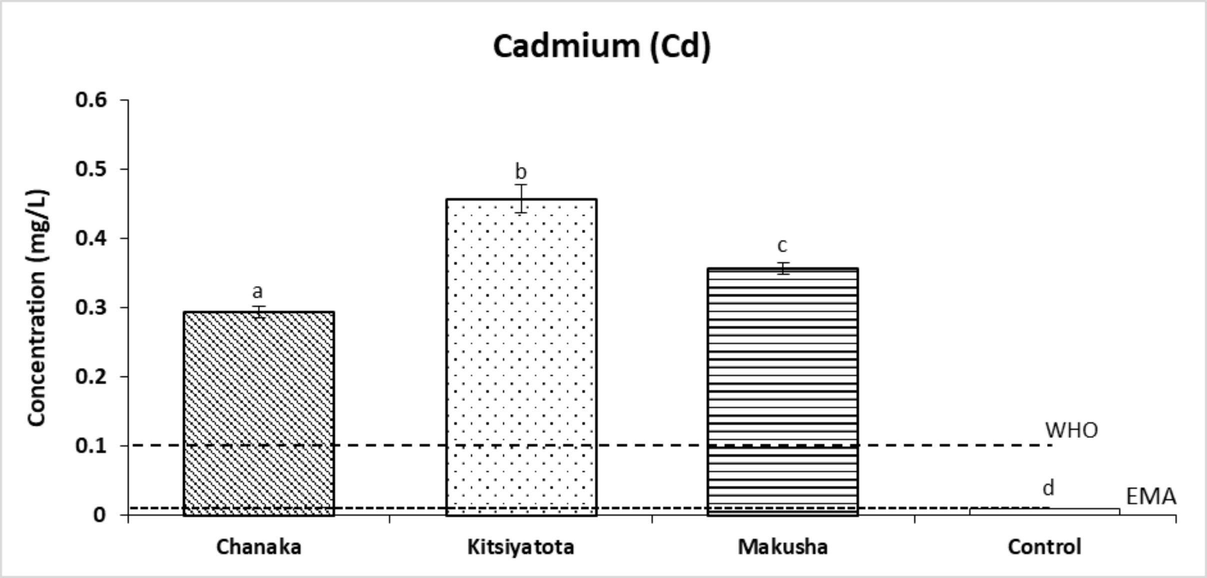

Fig. 4.1: Concentrations of Cadmium in ground water around three artisanal mines

All artisanal mining sites had Fe concentrations above EMA and WHO thresholds with Chanaka attaining the significantly highest Fe (2.17±0.02 mg/L) concentrations. The Fe concentrations declined in the sequence Control < Kitsiyatota < Makusha < Chanaka. Moreover, Chanaka and Makusha were not significantly different ($p > 0.05$) in Fe concentrations (Fig. 4.2).

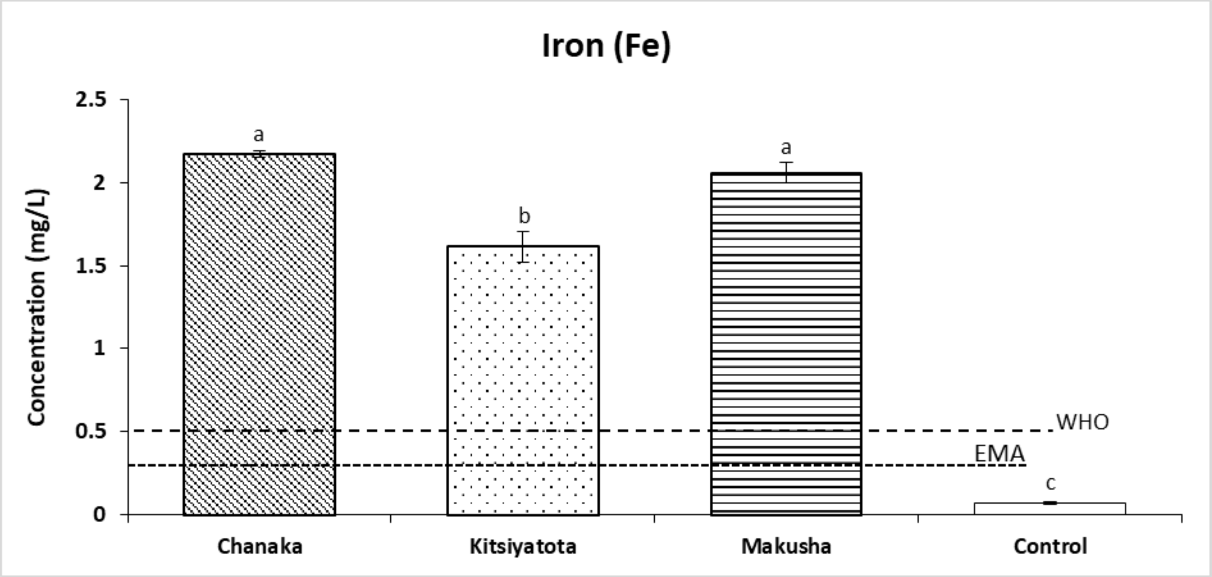

Fig. 4.2: Concentrations of Iron in ground water around three artisanal mines

The concentrations of Hg were above EMA and WHO standards in all the artisanal mining sites with Makusha recording the significantly highest Hg (0.43±0.01 mg/L) concentrations whereas no Hg concentrations were detected in the Control samples. All mining sites were significantly different in Hg concentrations ($p < 0.05$) with the Hg concentrations following the trend Chanaka < Kitsiyatota < Makusha (Fig. 4.3).

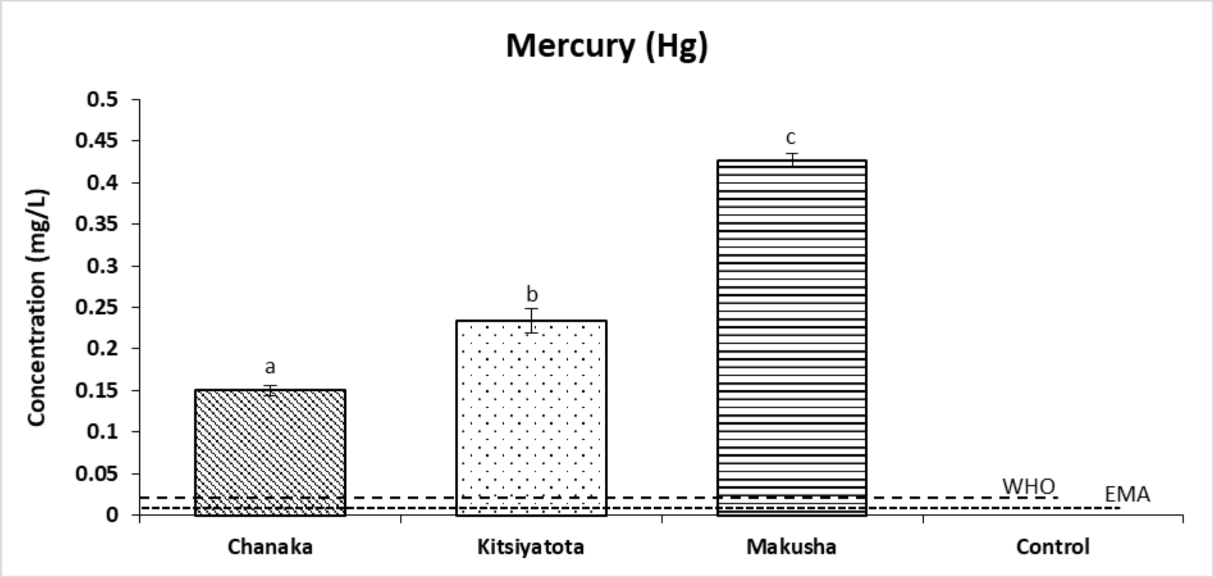

Fig. 4.3: Concentrations of Mercury in ground water around three artisanal mines

Kitsiyatota recorded the significantly highest Pb (0.27±0.01 mg/L) concentrations whereas Chanaka and Makusha were not significantly different ($p > 0.05$) in Pb. In addition, all mining sites had Pb concentrations above both EMA and WHO thresholds for groundwater (Fig. 4.4).

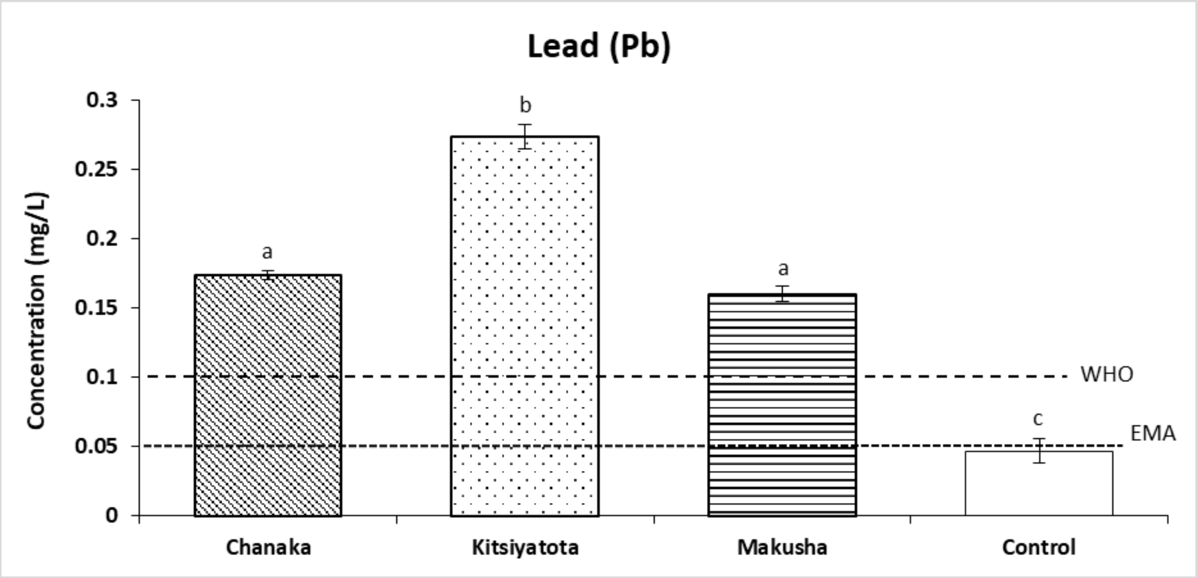

Fig. 4.4: Concentrations of Lead in ground water around three artisanal mines

The concentrations of Zn were highest in Kitsiyatota (0.38±0.01 mg/L) with Chanaka significantly different from other mining sites ($p < 0.05$). In addition, the Zn concentrations were above both the EMA and WHO limits (Fig. 4.5).

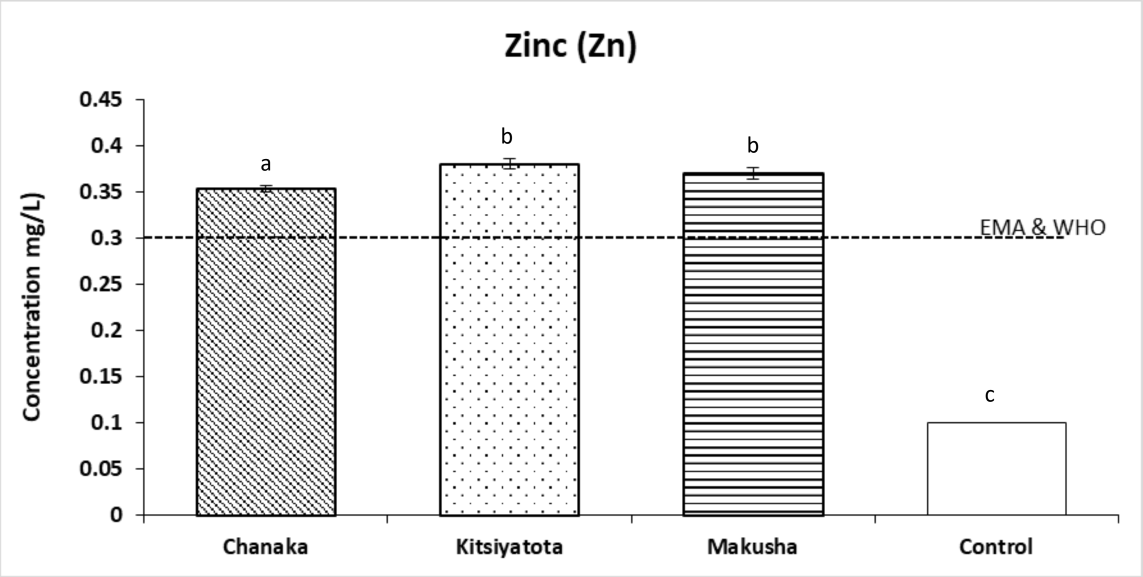

Fig. 4.5: Concentrations of Zinc in ground water around three artisanal mines

Overally, the total heavy metal concentrations in ground water decreased in the order Fe > Cd > Zn > Hg > Pb whereas by site comparison it followed the trend Makusha > Kitsiyatota > Chanaka > Control.

Chapter Five: Discussion

5.1 Groundwater quality

The characterisation of ground water parameters deduced that the water was a bit acidic with high BOD, COD, TDS and low DO content. High volume of vehicles and the use of petroleum fuels within the study sites results in leakages and seepage of fuel and oils into the soil which further infiltrates to the ground water. Results from this study are similar with those of Nwachuku (2014) who observed very low DO and pH in groundwater attributed to oil spillages. The oils contain hydrocarbons which are undegradable and persist in the environment over a long period of time (Acheampong *et al.*, 2013) reducing the amount of DO and create anaerobic activity in the ground water. Oil spills from mining activities may infiltrate the soil together with heavy metals thus affecting ground water. In most cases pollutants may be transported to other aquifers in the direction of groundwater flow (Ugwoha and Omenegwor, 2017). This reduces pH, DO content and increases the BOD, COD and turbidity of the ground water.

Comparison between sites showed that ground water in Chanaka and Makusha was slightly acidic which coulsd possibly haave emanated from AMD rendering the water unsafe for consumption. Ugwoha and Omenegwor (2017) stated that indicators of ground water contamination are low pH, low DO and high BOD compared with the WHO guidelines. In the present study, oil spills from vehicles and mobile equipment could have leached into the soil thereby contaminating ground water. As opined by Nwachuku (2014) groundwater pollution from oil spillages is not always amenable to total clean up. It is therefore safer and wiser to prevent its occurrence by eliminating disposal of toxic substances into the environment. Continued consumption of such contaminated ground water has the potential to cause harmful effects to humans. The likely clinical effects include kidney and liver failures, poor reproductive system, leukaemia and high blood pressure (Ugwoha and Omenegwor, 2017).

5.2 Trace element concentrations in groundwater

Several studies reported the presence of heavy metals in groundwater around mining sites (Xiao *et al.*, 2017; Chileshe *et al.*, 2020). The high presence of heavy metals in the sampled groundwater could have been a result of acidity which affects mobility of metals and readily dissolves them thus making them to occur at high concentrations (Chileshe *et al.,* 2020). Bielecka *et al.* (2009) asserted that heavy metals in soils are higher when the pH is acidic and lower when pH is 7.1-8.1. As observed in this study, pH was below 6 in soils and ranged from 5.9 - 7 in ground water.

As reported by Marhurapawar (2015), Cd has many uses e.g., in electroplating, batteries and metal coating. Traces of Cd observed in the present study emanate from battery residue derived from used batteries that are used in flash lights by the artisanal miners. Absence of proper solid waste storage facilities in the artisanal mining sites contributes to the batteries being dumped haphazardly leading to environmental contamination. Similarly, Mujere and Manuel (2016) reported higher concentrations of Cd in the upstream area of Revue River that were directly correlated with mafic and ultramafic rocks occurring in the area which contained significant Cd concentrations. The typical rocks occurring in the areas were mainly, basalts, gabbros, komatiites, peridotites and serpentinites.

The Fe content is resultant of the geology of the study area (Bindura) considering that it is made up of pyrite parent material derived from the greenstone belt that contains high Fe concentrations. As reported by Hassan *et al.,* (2017), Fe is the mostly found in the form of oxides and hydroxides when its ions (Fe^{2+} and Fe^{3+}) combine with oxygen and compounds containing sulphur. Thus, Fe dissolution will occur due to reduced pH brought about by AMD. In addition, Wiseman *et al.* (2015) deduced that bedrock is a source of Fe whereas elements like Cd and Pb emanate from anthropogenic sources. Similarly, Chileshe *et al.* (2020) reported high traces of Cu attributed to the parent geology which was a copper belt.

The high Hg concentrations observed in this study are similar to those of Mujere and Manuel (2016), as well as Mudyazhezha and Kanhukamwe (2014) who reported increased levels of Hg in Mazowe and Gwabalozi River respectively attributed to rudimentary methods of Hg amalgamation by artisanal miners. Likewise, Velasquez-Lopez *et al.,* (2010) asserted that the amalgamation technique used in gold recovery by the artisanal miners is responsible for the elevated concentrations of Hg in surface and ground water. The Hg is not soluble and thus cannot be recovered hence it is lost to the environment. This is worsened by the fact that illegal gold panning is also practiced without proper safety, health and environmental (SHE) quality standards. This leads to the leakage of Hg into the environment with potential adverse effects.

As observed in this study, Makusha was nearly three times the concentratons of Chanaka due to the high number of artisanal miners compared to Chanaka. Also, Chanaka contains registered artisanal miners unlike the illegal panners in Kitsiyatota and Makusha. Mujere and Manuel (2016) asserted that water pollution by Hg is one of the most pressing environmental problems in ASM, representing major environmental and human health concern in eastern and southern Africa. As such, exposure to acute levels can produce dysfunctional kidneys, unitary tract infection, vomiting, and, ultimately death (Pratush *et al.,* 2018; Gabriel *et al.,* 2019).

The presence of Pb traces in ground water from the present study is mainly attributed to automobile exhaust, particularly from leaded gasoline, motor vehicle tyres, and lubricant oils as heavy traffic volumes (Zwolak *et al.,* 2019) are deposited on to the soil and percolates into the ground thus affecting both soil and ground water quality. This concurs with Saxena and Saxena (2015) who reported elevated levels of Pb in agricultural soils derived from gasoline deposits close to highways. With agricultural activities in the vicinity of these artisanal mining sites, it becomes very risk as these pollutants affect soil quality which in turn reduces soil productivity and food security (Alloway, 2013). Also, pollutants may be extracted by crops via roots with detrimental effects along the food chain due to bio-magnification (Lei *et al.,* 2016).

Chapter Six: Conclusion and Recommendations

6.1 Conclusion

The findings of the present study indicated that groundwater around the artisanal mining sites had a low pH and DO content but had higher BOD, COD and TDS than the EMA and WHO permissible standards. The concentrations of heavy metals for both soil and ground water decreased in the order Fe > Zn > Cd > Pb > Hg whereas by site comparison the trend was Makusha > Kitsiyatota > Chanaka. As such, continued consumption of groundwater around Chanaka, Makusha and Kitsiyatota areas may cause some clinical effects due to the presence of trace elements. Though the concentrations were slightly above the set thresgolds, they may bioaccumulate overtime resulting in serious consequences.

6.2 Recommendations

- Continuous monitoring of groundwater should be practiced with adequate treatment before consumption.
- Artisanal mining sites should treat their effluent before disposal.
- Further studies should focus on ways of reducing groundwater contamination by artisanal miners.

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