University of Zimbabwe
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EFFECTS OF MINING ACTIVITIES AT BULYANHULU GOLD MINE (BGM) ON THE WATER QUALITY OF BULYANHULU RIVER: SHINYANGA - TANZANIA

By

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A Thesis Submitted in Partial Fulfilment of the

Requirements for the Degree of Master of Science Intergrated Water Resources

Management

June 2008

CERTIFICATION

The undersigned certifies that they have read and hereby recommend for acceptance by the University of Zimbabwe a thesis entitled: *Effects of Gold mining activities on the water quality of Bulyanhulu River*: The case of Bulyanhulu Gold Mine in Shinyanga, Tanzania in fulfillment of the requirements for the degree of Master of Science (Integrated Water Resources Management) of the University of Zimbabwe.

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DECLARATION

I, Grace Michael Nkuli, declare that this thesis is my own original work (except where acknowledged) and that it has not been presented and will not be presented to any other University for any other degree award.

Signature………………………………

Date………………………………….

ACKNOWLEDGEMENTS

Usually it is not easy for anyone to write a thesis of this length and importance in the given time without some external assistance. In view of this fact, I hereby whole heartedly thank the almighty God for everything and those in one way or the other, extended their help to me during the course of writing this thesis and so enabling me presenting in time to the respective Faculty of Engineering at the University of Zimbabwe. This work is a product of assistance, advices, guidance and counseling from different people, institutions, organizations and departments. I am indebted to all those who made the success of this work. Thanks for the University of Zimbabwe (Civil Department) and to “WaterNet” for a scholarship.

I wish to thank specifically my Supervisors Dr. Misi and Eng. Hoko (University of Zimbabwe) and Dr. Kimwaga (University of Dar es Salaam) for their determined supervision. Their advice and guidance from proposal write-up, presentations, fieldwork, laboratory work, data analyses and thesis write-up to submission are highly appreciated. Special thanks to Prof. M.A. Kishimba, Head of ANCAP at the University of Dar es Salaam for his assistance, encouragement and advice. My fellow postgraduate students whose relevant academic material I had access to especially Miss Hazel Mphande you are a wonderful friend.

Sincere thanks to the Bulyanhulu Gold Mine (BGM) Management for allowing me to do my research at BGM and by providing facilities, guidance and support for the whole period of my study in particular the General Manager Mr. Greg Walker, Environmental Manager Mr. Shoo Korodias, Human resources Manager Mr. Gervas Chapalwa, GIS specialists Ernest Kika & Genes Mkumbo, EHS Manager Mr. Juma Malunga, Environmental coordinator Mr. Thobias Mathew, Officers Mackenzie Bujiku, Freddy Mkisi, Angelo Kitula, Bertha Johnson, Simon Mwaluko, Nura Kalegeya and all members of staff who also assisted in doing the research.

Acknowledgement is also due to Barrick Analytical laboratory; in particular to Mr Ashok Kumar (Chemist), T. Bahemuka (Chemist) and D. Salum (Chemist) for making my work possible by giving me water analysis practical training and their technical assistance in the laboratory. I would also like to thank Mr. Sephton Ross for his guidance and assistance in reviewing the BGM Water Quality Programme.

Finally, yet very special, my heartfelt acknowledgement to my husband Mr. Martin L. Mgallah for his love and patience in missing my presence for most of the time I was carrying this study, my family as a whole, relatives and friends for their very strong encouragement, perseverance and support. I can not mention all as the list is endless; however my heart-felt thanks are extended to all those who in one way or another contributed to make the completion of this hard and long work possible.

DEDICATION

This dissertation is dedicated to:

My Loving Parents
Modesta and Michael

The Family of
Mr. & Mrs. Mlolwa

My Husband
Martin

My Sister
and

My Brothers

ABSTRACT

This study assessed the effects of mining activities at Bulyanhulu Gold Mine (BGM) on the water quality of Bulyanhulu River in Tanzania. Potential pollutants were identified, quantified and their spatial distribution determined along different sampling points upstream and downstream the mine. The water quality of the river and groundwater in the area is of importance as the water is used for agriculture and domestic purposes. Grab samples were collected from Bulyanhulu River, shallow wells, Effluent Control Ponds (ECP's) and boreholes during the period January-March 2008 and analyzed for Temp, pH, EC, SO_4^{2+}, Fe, Ni, Ag, As, Hg, CN^-, NO_3^- and Zn according to Standard methods.

The pH values in water samples were 6.3 ± 1.4 in ECP, 7.0 ± 0.2 in river, 5.9 ± 0.4 in boreholes and 5.2 ± 0.3 in wells. The conductivity in ECP, river, boreholes and wells sample were 1969 ± 470 µS/cm, 207 ± 46 µS/cm, 1023 ± 497 µS/cm and 203 ± 112 µS/cm respectively. The mean SO_4^{2+} concentrations in ECP, river, boreholes and well sample points were 1014 ± 353 mg/l, 70 ± 30 mg/l, 497 ± 205 mg/l and 181 ± 0 mg/l. The temperature values were 26 ± 1 °C for ECP, 24 ± 1 °C for the river, 25 ± 1°C for boreholes and 24 ± 1 °C for wells. Values of NO_3^- for ECP were 5 ± 1 mg/l, 4 ± 2 mg/l for river, 5 ± 3 mg/l for boreholes and 4 ± 3 mg/l for wells.

Results for Ag were 0.1 ± 0.1 mg/l for ECP, 0.1 ± 0 mg/l for the river, 0.1 ± 0 mg/l for boreholes and <0.005 mg/l for wells. Results for Ni were 0.7 ± 0.3 mg/l for ECP, 0.4 ± 0.3 mg/l for the river, 0.04 ± 0.03 mg/l for boreholes and 0.2 ± 0.1 mg/l for wells. Concentrations of Fe for ECP were 7.2 ± 3 mg/l, 2.9 ± 0.13 mg/l for the river, 0.3 ± 0.4 mg/l for boreholes and 0.2 ± 0.13 mg/l for wells. Concentrations of Zn in ECP, river, borehole and well samples were 13.0 ± 7.0 mg/l, 1.8 ± 0.8 mg/l, 4.0 ± 2.0 mg/l and 2.5 ± 0.8 mg/l.

Water quality of the Bulyanhulu River, shallow wells and monitoring boreholes were compared against Tanzanian maximum permissible concentration and WHO drinking water quality guidelines while Effluent Control Pond values were compared against the Tanzanian effluent discharge maximum permissible concentration guidelines. The concentrations of As, Hg and CN^- were low (below method detection limit).

The high concentrations of these parameters could be attributed to weathering of sulphide ore bodies, chemicals used in the process plant, decomposition and leaching of discarded batteries and old metal scraps in mine areas. These elements could relatively have high toxicological effects in the environment, biota and health hazards to human beings especially in the mining communities.

It was concluded that, the water quality of the river is polluted with respect to Ni, Fe and slightly by Zn and was therefore, considered not suitable for human consumption. Groundwater quality was affected by mining activities with respect to pH, EC, SO_4^{2+}, Ni and Zn however; EC and SO_4^{2+} affected the boreholes more. The ECP's showed highest mean concentrations of all elements studied. It is therefore, recommended to treat the effluents in the ECP's by precipitating out metals thus reducing their mobility through seepage. The existing monitoring Programme for BGM needs improvement.

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ABBREVIATIONS AND ACRONYMS

AMD	Acid Mine Drainage
ANFO	Ammonium Nitrate and Fuel Oil
ARD	Acid Rain Drainage
ATSDR	Agency for Toxic Substances and Disease Registry
BGM	Bulyanhulu Gold Mine
BOT	Bank of Tanzania
CSM	Conceptual Site Model
DEM	Digital Elevation Model
DNA	Deoxyribonucleic acid
EDDS	Ethylenediamine Disuccinic Acid
EDTA	Ethylene Diamine Triacetic Acid
E_h	Redox Potential
EIA	Environmental Impact Assessment
EIS	Environmental Impact Statement
EMP	Environmental Management Plan
EMPA	Environmental Management and Protection Act
EMPC	Effluent Discharge Maximum Permissible Concentration
EPA	U.S. Environmental Protection Agency
GDP	Gross Domestic Product
HDPE	High Density Poly Ethylene
ICP	Inductively Coupled Plasma
ILO	International Labor Organisanition
IWRM	Integrated water resources management
LVGF	Lake Victoria Gold Field
MDG's	Millenium Development Goal's
MIBC	Methyl Isobutyl Carbinol
NDGRP	National Strategy for Growth and Reduction of Poverty
NEMC	National Environmental Management Council
OSHA	Occupational Safety and Health Administration
PAX	Potassium Amyl Xanthate
RMPC	Receiving Maximum Permissible Concentration
SOB's	Sulphate oxidizing bacteria
SOP	Standard Operating Procedure
TWL	Tanzania Water Law
URT	United Republic Of Tanzania
UTM	Universal Transverse Marcator
WHO	World Health Organization

CHAPTER ONE

1. INTRODUCTION

1.1 Background information

Water is one of the most essential constituents of the human environment. The water resources generate development in socio-economical issues crucial to the society in general and more specifically for industries, agricultural activities and for the public use. Although it is agreed that water is an economic good, it is also a social good, finite, non-substitutable and vital to all forms of life (ICWE, 1992). The last three elements make water not just like any other commodity but a good that should be conserved and treasured. Integrated water resources management (IWRM) is an essential approach to water resource management it emphasizes on the effective management of water resources within the catchment. There are different activities (such as mining) that occur within a catchment that use and affect water resources. The impacts of mining activities for instance, can create problems for ecosystems functioning. IWRM approach seeks to promote the coordinated management of water resources to maximize water's social, economic, and environmental value to society, based on essential considerations of equity, efficiency and environmental sustainability (GWP-TAC, 2000).

Mining activities that affect water quality include the disposal of waste rock, tailings deposition, and effluent discharges from different stages of mineral processing (Dock, 2005). Koryak (1997) argues that the effluent produced from waste rock dumps has a potential to cause Acid Rain Drainage (ARD) into stream and river waters. McMenemy (2001) reported the non-survival of fish in Ely Brook River - USA due to extremely poor survival and growth conditions resulted from mine effluent.

Tailings are usually in the form of fine slurry, which are managed in ponds. Both the chemical and physical stability of tailings management facilities are of high importance, since they can also have an ARD potential. The amount of tailings generated depends on the content of the desirable mineral(s) in the ore, its grade, and the efficiency of the mineral processing stage in the recovering process. The United States Environmental Programme affirms that mine tailings contain residual minerals and potentially toxic chemicals (Wood, 1981).

According to Ripley (1996) effluent released from gold mines is mainly constituted of heavy metals from sulphides and silicates in which they are originally bound within the ore bodies as pyrite (FeS_2) and chalcopyrite ($CuFeS_2$). The metal and other toxic organic and inorganic chemicals are liberated during the ore size reduction in the process of recovering the desired mineral. When released in significant quantities that exceed the cleansing capacity of water, these pollutants give rise to a number of deleterious environmental effects that can change the ecosystems in streams and rivers (Marcello *et al*., 2000).

Gold mining operations can have negative impacts on both society and the environment (ILO, 2001). Uncontrolled mining operations can be a source of heavy pollution to soils, water, sediments and air and can cause deforestation, soil erosion, river siltation and landscape destruction, health hazards of exposure to toxic dust, chemicals, noise and vibrations, poor working environments including extreme heat and humidity and the outbreak of a number of communicable diseases such as HIV/AIDS, accidents from rock fall, explosions, floods and destruction of the ecosystem that affect species biodiversity.

However, mining contributes to the revenue of countries, increase the Gross Domestic Product (GDP) and foreign exchange earnings. A major objective of the mining sector policy in Tanzania is to alleviate poverty in the country by creating gainful and secure employment in the mineral sector and by providing alternative sources of income (particularly for the rural population) and to ensure environmental protection and management (ILO, 2001; MMSD, 2002). Philips *et al.* (2001) and BOT (2002) have also documented positive aspects of mining which include; creation of employments and poverty relief, contribution to Government revenues, foreign exchange earnings, tourism attraction, improvement of the infrastructure, source of ornamentals, jewelleries and increase of Gross Domestic Product (GDP). Contribution of the mining sector to the GDP in Tanzania increased to 3.8% from 3.5% registered in 2005 (URT, 2007).

The Bulyanhulu Gold Mine (BGM) is confined to the Lake Victoria Gold Field (LVGF) at the confluence of Bulyanhulu River. Lake Victoria Gold Fields (Fig.1) are the largest and richest gold fields in Tanzania. They have a long history of gold mining, which dates back to the 1920's. Consequently mining has had profound environmental impacts on the Lake Victoria catchment areas (Kahatano *et al*., 1995).

The surface drainage from the Bulyanhulu Gold Mine is towards the direction of Bulyanhulu River, which is the major surface water body in the area. BGM discharges its effluent intermittently into this river, which flows into Lake Victoria at Smith sound on the southern end of the Mwanza Gulf. Mwanza Gulf is one of the major inlets to Lake Victoria that extends over 70 km inland. According to Shuttle (2005) the sulphide minerals mined at Bulyanhulu Gold Mine are mainly pyrite (FeS_2) and chalcopyrite ($CuFeS_2$). If these minerals are not well managed they can affect the quality of effluent released to the Bulyanhulu River. Malunga (2007) indicates that due to heavy rainfalls there have been a number of accidental effluents discharges from the mine effluent ponds to the environment in the year 2002 and 2004 to 2007. For instance, in 2005 approximately 450,000m^3 of effluents was discharged into the river.

A study conducted by NEMC (1994), on heavy metals pollution in gold mining areas in the Lake Victoria zone, revealed that mercury levels were significantly higher than the WHO (1998) permissible level of 1µg/l in drinking water. Work by Kahatano *et al*. (1995) also found high levels of Pb, Cu, Cr, Zn and Hg in water of some streams and rivers in the Lake Victoria Gold Fields. Possible sources of these metals include mining activities especially artisanal mining, industrial discharges and traffic road runoff (Kishe and Mahiwa, 2001).

In addition there are a number of human activities within the BGM vicinity that have likely resulted in impacts on aquatic resources, including those associated with settlement, agriculture, and artisanal mining. These activities require water extraction from the local drainages they increase sedimentation of rivers, and may contribute high levels of nutrient rich agricultural runoff to aquatic systems. However, artisanal mining may pose the most serious local threat to the environment, due to the unrestricted use of mercury amalgamation in the gold extraction process.

Fig.1. Map showing the location of Lake Victoria Gold Fields in Tanzania (Source: Malunga, 2007)

1.2 Problem statement

The effect of gold mine activities on surface water quality (rivers) have been investigated by a number of researchers in many parts of the world; they generally acknowledge water quality deterioration due to the discharge of partially or untreated mine effluents, and/or accidental discharges, which can change the chemistry of water (McKinnon, 2002 ; Kaye, 2005).

Regardless of the accidental mine effluent discharges reported by Malunga (2007) from BGM Effluent Control Ponds (ECP) to the environment, none of the previous scientific studies has attempted to assess the water quality of the Bulyanhulu River, the residential shallow wells and the quality of mine effluent ponds despite the potential of pollution water sources during flood events. These ECP are man made pollution control ponds exposed to runoff from BGM tailings and waste rock dumps. It was necessary to analyse the quality of water in them because they have a potential to affect the Bulyanhulu River and the local groundwater quality through seepage and infiltration. The study wished to establish water quality database for Bulyanhulu River. The data would be used to assess any changes in water quality and to assist environmental law enforcers and policymakers in coming up with strategic pollution abatement measures. This study therefore, intended to provide answers to this apparent gap in knowledge.

The study is of great relevance to water quality monitoring studies in Tanzania, due to the limited amount of information concerning the effect of mining activities on water quality in the country. This will also provide necessary information in the Integrated Water Resources and Management (IWRM) cycle especially in implementing its principles. The implementation of IWRM in Southern Africa countries has focused on: Changing water law and policy, managing water along watershed boundaries, implementing economic measures for cost recovery and stakeholder's participation (GWP-TAC, 2000). Therefore, the water quality data obtained from the Bulyanhulu River by the study would be used as primary data for managing water along the Bulyanhulu River sub-catchment.

1.3 Justification

According to Norecol and Moore (1997) the approximate catchments area of Bulyanhulu River is 294 km^2. It was important to conduct this study because the water quality of Bulyanhulu River is of primary concern as it supports activities such as agriculture and domestic uses for the population around of approximate 30,000-50,000 people. Bulyanhulu community depends on water from this river and shallow wells of about 5-10 m deep for domestic use, which are potentially prone to contamination from mining activities (Large and artisanals).

NEMC (1994) and Kahatano *et al*. (1995) fieldwork reports revealed high distributions of heavy metals pollution in some streams and rivers in the Lake Victoria Gold Field (LVGF), which has extremely affected the ecological health of the Lake. Bulyanhulu River is also one of the rivers in the LVGF and is a likely source of poor water quality into the Lake Victoria. The water of Lake Victoria and its catchment is a shared resource between three countries: Tanzania, Kenya and Uganda. The water is used for public water supply, hydropower generation, fisheries, industrial, agricultural uses as well as recreational purposes. The activities causing pollution in the lake include: human settlement, deforestation, intensive farming, livestock keeping, wetlands encroachment, urban agriculture, gold mining and infrastructure (World Bank, 1996). In absence of proper water management in the catchments, conflicts within countries often arise from competing water users, which could lead to scarcity. Continued water scarcity that is experienced in most Southern African countries, necessitates the adoption of IWRM approach. Observation from the Kihansi River catchment in Tanzania has demonstrated mounting conflicts and competition among water users. Therefore, it was important to assess the current state of the heavy metals and non-metallic constituents of the river water and whether the mining activities impacts on the local water quality or not and if so to what extent.

1.4 Objectives

1.4.1 General Objective

To investigate the current state of specific heavy metals and non metallic parameters of water quality and to determine the impact of mining activities on water quality within Bulyanhulu River sub-catchment, Tanzania.

1.4.2 Specific Objectives

1. To identify the sources of pollutants emanating from BGM mining activities.
2. To quantify the pollutants from mining operations at BGM that contributes to poor water quality.
3. To map the spatial variation of the concentration of pollutants at different sampling sites within the Bulyanhulu River sub-catchment.
4. To review the current water monitoring system currently in place at BGM.
5. To propose improved management strategies for controlling pollutants at BGM.

1.5 Scope of the study

For the purpose of this study only specific heavy metals and non-metallic parameters were investigated, as they were considered to be the most pertinent to the evaluation of water quality with respect to gold mining. The inclusion of other parameters such as biological parameters (DO and BOD) is feasible, but was beyond the scope of this study. The study also focused only on the point sources of pollution from mine drainage. However, the use of explosives in underground mining, the scattering of old and discarded lead-acid batteries and the chemicals used in extracting gold may also contribute to water pollution during heavy rain y seasons.

CHAPTER TWO

2. LITERATURE REVIEW

According to Dock (2005), mining is one of mankind's oldest industries. This industry has a significant history throughout the world. The purpose of mining is to meet the demand for metals and minerals resources to develop infrastructure and to improve the quality of life of the population, as the extracted substances are the raw materials for the manufacture of many goods and materials.

Mining activities generate effluent containing a number of chemical pollutants, which adversely alter the quality of both surface and groundwater resources that often cause significant pollution (Koryak, 1997). While Ellis (1989) suggests that the effect of degraded water quality is not only felt in the local area of the mine, but often felt downstream of the mine far away from the source of pollution, Harrison (1990) argues that, as pollutant is introduced into a water source such as a river, the concentration of the specific pollutant is initially high, owing to the ability of a river to disperse a pollutant as a result of the river's flow. However, the concentration of the pollutant becomes less and less as the pollutant moves further away from its point of introduction.

Degraded water quality has an effect on the aquatic life in the river or lake (Loeb and Specie, 1994). It may also impact on the agricultural sectors of the area, if the degraded water is used for irrigation or livestock consumption. This could be disastrous for farmers who rely on the degraded river as a main source of water, because the reduced water quality could potentially have a detrimental effect on crop yield and impact on livestock health (Harrison, 1990).

2.1 Gold Mining in Tanzania

The Government of Tanzania embarked on economic reforms and restructuring between the mid 1980s and the 1990s in order to attract investors (URT, 1997). These reforms marked a clear shift in favour of private sector development and market oriented economic management. In these new reforms the role of the government has been re-defined from that of owning and operating the mines, to that of only providing policy guidelines, stimulating private investment and providing support for investment. The reform is in line with the Mineral Policy of Tanzania (1997), Mineral Act and Fiscal Package of 1997 (URT, 1997). Thus, since 1998 Tanzania has been opening gold mines every year. Currently the country has mining investments worth over 1 billion US dollars and boasts seven modern gold mines namely; Bulyanhulu, Tulawaka, Geita, Nzega, Buhemba, Buzwagi and Placer Dome. Most of these gold minings take place in the LVGF. When fully operational, annually they produce 1,500,000 ounces of gold worth more than 400 million US dollars annually (Mbilinyi, 2004).

Environmentalists from Tanzania and Uganda have clearly expressed their concern regarding gold mining activities close to Lake Victoria, because the ecological health of the Lake has been severely affected by a combination of degrading processes of different nature from mining effluents (Mwalyosi and Hughes, 2004). They have also warned that, there is a high risk that chemicals such as (sodium cyanide) used to extract gold from ore are poisonous might flow into the Lake.

2.2 Pollution Control Regulations in Tanzania

The government of Tanzania had determined, since independence, to protect and improve the quality for the welfare of her people. However, much concern was on potable water for public consumption. The government has a fully-fledged Division of Environment that deals with all matters concerning the environment. The Ministries of Water and Livestock Development, Agriculture and Food Security, Lands and Human settlements Development, Health, Natural Resources and Tourism; all these have been engaged with water resources issues either directly or indirectly. The National Environmental Management Council, (NEMC), is the governmental parastatal organization affiliated with the Office of Vice President. It coordinates the activities of all bodies concerned with environmental matters and serves as a channel between these bodies and the government.

The Environment Management and Protection Act (EMPA) of 1997 is the statute that controls the discharge of mine effluent into the environment (URT, 1997). Tanzania water law for effluent and mining regulation for effluents acts to control an Act of Parliament and it uses the Pollution Control Unit as its organ to monitor water pollution and compliance by the key polluters of the environment (URT, 1997). The Act incorporates the polluter pays principle. According to Mwalyosi and Hughes (1998), the Acts requires each mine to hold valid permits for each of its effluent discharge sites including the tailings dam because of their potential to cause surface and groundwater pollution. As part of the permit requirements, mines are required to submit water samples on quarterly basis to the Government laboratory for chemical analysis to find out if they are complying with the set standards.

The National Environmental Policy of 1997 recognizes the need for a multi-focus approach in the management of water. It recognizes the existing institutional mechanisms and seeks to enhance coordination and cooperation of the institutionally distinct bodies with overlapping mandates. In so doing, the policy recognizes the Ministry responsible for water as “the authoritative voice and catalyst for action on behalf of the entire Government”. As the policy guidance institution, the Ministry is expected to be an overseer for the implementation of policies under the jurisdiction of line ministries. This is achieved through the Ministry providing support and influencing line ministries in carrying out their mandates. Under this set-up sector Ministries are expected to represent constituencies of the Ministry responsible for water with an informed voice and commitment to environmental outcomes (URT, 1997).

The policy regards local authorities as direct channels for people to express their concerns and be able to take action for creating sustainable conditions. As such, they shall be responsible for overseeing planning processes and establishing local water policies and regulations. They are regarded as being well placed to provide education, mobilize and respond to public water and environmental concerns. At the Regional level, there are “Policy Committee on water” composed of District Commissioners and chaired by the Regional Commissioner. Its work shall be facilitated by District, Ward and Village Committees on water and the environment under the auspices of the District, Ward and Village councils respectively. The Regional Committee is expected to deal with matters affecting the water and environment in the region and provide guidance or propose policy measures and actions (URT, 1997).

The Tanzanian guidelines for water quality serve as the primary source of information for determining the water quality regulations of different water uses and for the protection and maintenance of the health of the aquatic ecosystem (URT, 1998). These guidelines form an integral part of the water quality management strategy to maintain Tanzanian's water resources fit for use. Table 1 shows the prescribed receiving water guidelines for parameters used in the present study.

Table 1: Tanzanian guidelines for effluent discharge and drinking water quality

Parameter	*Units*	*Effluent*	*Receiving water*
		MPC	*MPC-Category 1*
pH		6.5 - 8.5	6.5 - 8.5
Conductivity	µS/cm	400	400
Sulphate	mg/1	600	600
Nitrate-N	mg/1	50	50
Cyanide-Total	mg/1	1	0.5
Arsenic	mg/1	0.2	0.05
Iron	mg/1	3	1
Mercury	mg/1	0.005	0.001
Nickel	mg/1	0.5	0.05
Zinc	mg/1	1	0.2

(Source: GOT, 2006)

Note: According to Act No. 10, MPC = Maximum Permissible Concentration, for receiving water as given in the (Amendment) Water Act, 1981: for effluent discharge given in the Tanzanian Standard General Tolerance Limits for Municipal and Industrial Wastewaters. Maximum Permissible Concentration (MPC) Category 1: Water suitable for drinking water supplies, swimming pools, food and beverage manufacturing industries, pharmaceuticals manufacturing industries or industries requiring water of similar quality.

2.3 Sources of pollution in Gold mining and its effects on the Environment

For effective monitoring and control of pollution, a clear understanding of pollution sources is essential (Ellis, 1989). There are several sources of pollution from which potential pollutants may enter surface and groundwater sources. However, they can be categorised into two main groups namely: point sources and non point sources. According to Hoko (2007) point sources of pollution is characterized by a single or discrete conveyance such as domestic wastewater discharge, wastewater discharge from industries and mine drainage and non-point sources of pollution involve large and dispersed sources of contamination like agricultural runoff, erosion from tillage, runoff from landfill, livestock, human waste etc. Ellis (1989) noted that water pollution from mines arises from five principle sources namely; mine drainage, water from gold processing, runoff from stockpiles, runoff from spoil heaps and surface drainage. Liquid effluent released from gold mines can constitute high concentration of heavy metals such as cadmium, arsenic, manganese, lead, antimony and organics such as nitrates, phosphates, and sulphates just to mention a few of the constituents. When released in significant quantities that exceed the cleansing capacity of water, these pollutants give rise to a number of detrimental environmental effects (Marcello *et al*., 2000).

2.3.1 Mine drainage pollution on water sources and the environment

According to Benner *et al*. (2002) the most serious and pervasive environmental problem related to mining waste is acid mine drainage (AMD) caused by effluents from waste rocks and tailings. Ravengai *et al*. (2004) urges that acid generation occurs when sulphide rich materials, mainly pyrite (FeS_2) and pyrrhotite (FeS) in the presence of catalysing bacteria, such as *Thiobaccilus ferroxidans* are exposed to air and water and are oxidised to form sulphuric acid. The sulphuric acid, which is generated, easily dissolves metals such as iron, copper, aluminium, and lead (Koryak, 1997). AMD is characterized by depressed pH range of 2-4.5 and elevated concentrations of dissolved heavy metals (Genske, 1996).

The effects of AMD on streams have been documented for many years. In 1906 a large fish kill on the Allegheny River below the Kiskiminetas River confluence in USA was caused by AMD (Lewis, 1906). While Dallas and Day (1993) found that the combination of acidity and dissolved contaminants kills most forms of aquatic life, rendering streams nearly sterile and making water unfit for human consumption, Needham and Books (1997) suggest that potential problems caused by AMD include impacts on mine water quality by limiting reuse of mine water and process water and creating corrosion problems for mine infrastructure and equipment, impact on riparian flora and faunal communities (e.g. death of trees) along the downstream channels and around the source of AMD, impact on groundwater quality, particularly in shallow aquifers, impairment of beneficial use of waterways downstream of mining operations for purposes such as stock watering, recreation, fishing or irrigation and difficulties in re-vegetating and stabilising mine waste.

A study by William *et al*. (1996) on 270 mine discharges in the Stonycreek River in Pennsylvania found that many of the discharges had a pH less than 3.0. Water samples from these discharges generally had high concentrations of acidity, iron, manganese, aluminium, and sulphate thus negatively degrading aquatic habitats. According to Koryak (1997) stream bottoms covered with orange or yellow-brown iron oxide or white aluminium oxide precipitates can be toxic to benthic algae, invertebrates, and fish as the bottom dwelling organisms are particularly sensitive to AMD precipitates .

Based on the reported effects of AMD, it can be deduced that failure to control discharges may cause spills and damage to the surrounding environment (Marcello *et al*., 2000). Moreover, water resulting from the waste rocks and tailings may create leachates when seeping (essentially in respect of tailings from ferrous and non-ferrous ores). The creation of leachates gives rise to sulphide, production of soluble salts and heavy metal migration to the surrounding environment, as well as the leaching of residual process chemicals in the tailings such as cyanides, acids, and alkalis. These can also result from seepage through and below impoundment walls, percolation to the subsoil and groundwater or overflow of the dam walls or spillways. Once the process of acid generation has started, it is extremely difficult to stop.

2.3.2 Heavy Metals

Preliminary investigations by NEMC (1994) and Kahatano *et al*. (1995) on surface water quality in the Lake Victoria Gold Field revealed that poor water quality was a result of mainly heavy metals from gold mining activities. The term heavy metal denotes, elements belonging to the group of transition elements in the Periodic Table having atomic weights about 63 and to about 201 that occur in low abundance in the environment (Duffus, 2002). Heavy metals generally have specific gravities greater than 4.0 (Connell *et al*., 1984).

The main sources of heavy metal pollution in water are associated mainly with mining operations, domestic sewage, industrial wastes, oil spills, combustion emissions, metallurgical activities and garbage dumps (Duffus, 2002). When the rate of mining of a certain given element exceeds the natural rate of recycling by a factor of ten or more, then the element is considered a potential pollutant (Pendias and Pendias, 1994).

Background levels of heavy metals such as Cadmium, Lead, Arsenic and Mercury among others, in soils and waters in the absence of anthropogenic additions and enriched rocks are relatively low and do not cause pollution problems (Odero, 1998). Pollution arises when the concentration levels exceed the established environmental tolerable levels as a result of additions and enriched natural sources, increasing the quantity and distribution of heavy metals in the atmosphere, on land and aquatic environment (Odero, 1998).In one study by Kahatano *et al*. (1995) found high levels of heavy metals in water of some rivers in the Lake Victoria Gold Fields likely to originate from mining effluents within the area and natural processes such as soil erosion and weathering. Hamza (1996) also found similar. The levels of Chromium, Copper, Lead and Zinc in the Lake Victoria found by Hamza (1996) are summarized in Table 2. Normally heavy metals do not exist in soluble forms for a long time, they may be associated with suspended colloids that may finally settle down. Therefore, high concentrations of heavy metals in bottom sediments are most often an adequate indication of water pollution (Pendias and Pendias, 1994).

Table 2: Mean heavy metal concentrations in water samples drawn from Lake Victoria

Water source	*Metal concentrations in (mg/l)*			
	Zinc	*Chromium*	*Copper*	*Lead*
Mwanza North	200.2	13	10.1	9.4
Mwanza Central	110.8	2.2	9.9	2.9
Mwanza South	104	2.9	6	7.5

(Source: Hamza, 1996)

- **Mercury (Hg)**

In 1953 the first outbreak of Minamata disease occurred in Japan due to Methyl Mercury discharged in the effluent of a nearby vinyl chloride factory. Methyl-mercury bio accumulated in fish, the main component of the diet for many local residents, of which 397 cases and 37 deaths were recognized (George, 2001). Mercury effects arise from dysfunction of the Central Nervous System with clinical signs characterized by numbness in arms and legs, blurring and even loss of vision, loss of hearing and muscle coordination and lethargy and irritability. Other incidences occurred in Iraq (1960), Guatemala (1963-1965) and Pakistan (1969). A major outbreak occurred in Iraq in 1971-2 following the delivery of more than 95,943 metric tons of seed grain to rural farmers that contained an average of 7.9 mg/l Methyl Mercury (George, 2001). The poisoning occurred because the farmers made flour from the grain instead of planting it, hence at least 6,350 patients were admitted to hospitals, where 459 of them died (Bakir *et al*., 1996). The recommended limit by World Bank standards for mercury effluent release is 0.002 mg/l.

- **Nickel (Ni)**

Nickel originates from Arsenide and Sulphide ores (Lawrence *et al*., 2004). It is deposited in rivers and streams through discharges of effluents from mining operations. It is exposed to human, animals, and birds through drinking contaminated water and inhaling of dust from the atmosphere. Its health effects include the disturbance of respiratory system and asthma, birth defects, vomiting and damage of Deoxyribonucleic Acid (DNA) at high concentrations. Lawrence *et al*. (2004) reported negative effects of nickel on phototropic organisms such as *algae*, *cyanobacteria* and on workers who accidentally drank light green water containing 250 mg/l of nickel from a contaminated drinking fountain. The workers had stomach aches and suffered adverse effects in their blood (increased red blood cells) and kidneys (increased protein in the urine). This concentration of Nickel is more than 100,000 times greater than the amount usually found in drinking water.

Occupational Safety and Health Administration (OSHA) has set an enforceable limit of 0.001 mg/l of Nickel for metallic nickel and nickel compounds in workroom air to protect workers during an 8 hour shift over a 40 hour workweek. EPA recommends that drinking water levels for nickel should not be more than 0.1 mg/l (ATSDR, 2005). However, the required effluent standard set by World Bank is 0.5 mg/l.

- **Cyanide (CN^-)**

Goyer (1995) urges that Cyanide is a highly toxic chemical that is used to recover precious metals, primarily Gold and Silver (from low grade ore) bodies. Cyanide in water exposed to sunlight is degraded to less toxic compounds such as carbon dioxide, nitrate or ammonia. However, it tends to react readily with many other chemical elements and is known to form hundreds of different compounds. Although these are generally less toxic than Cyanide, they are still known to be toxic to aquatic organisms and may persist in the environment for long periods of time. Some of these compounds may accumulate in plant and fish tissues (Goyer, 1995).

In a report by MPC (2000) reported that the Nevada's Carlin Trend Mine released over 3.5 billion pounds of toxic chemicals, such as Cyanide, Arsenic, Mercury and Sulphuric acid, among these Cyanide is extremely toxic. Cyanide poisoning can occur through inhalation, ingestion and skin or eye contact. One teaspoon of a 2% solution by volume can kill a human. In general, fish and other aquatic life are killed by cyanide concentrations in the microgram per litre range, whereas bird and mammal deaths result from cyanide concentrations in the milligram per litre range (MPC, 2000). The allowable limit for effluent release containing cyanide in most countries is in the range of 0.2 -1 mg/l (Antamina and World Bank, 2005).

A significant disaster occurred in Romania at Aural gold plant in January, 2000 where 3.5 million cubic feet of cyanide-contaminated waste entered the Tisza River, eventually poisoning the Danube River and infected over 250 miles of rivers in Hungary and Yugoslavia. It killed thousands of fish and made a significant portion of the Tisza River watershed undrinkable and hostile to aquatic life (UNEP, 2000). Knight (2001) reported livestock and human death in less than 24 hours after using water from the stream near Geita Gold Mining in Tanzania, the deaths were linked to the mine. This was reported to be due to overflow of mining waste from the 82-hectare effluent dam into nearby streams.

- **Zinc (Zn)**

According to Dock (2005), Zinc is one of the toxic heavy metals commonly released by mining. Zinc is used in galvanizing and alloying. It has been associated with impairment of river and stream water quality. For instance, it was reported by the State of Texas USA (2005) that Neeches River above Lake Palestine was not meeting its requirements for aquatic uses due to high level of Zinc that exceeds a legal limit of 5 mg Zn^{2+}/l stated by the World Health Organization. High concentrations of Zinc are associated with reduction in aquatic species diversity and abundance (Peplow, 2000). Zinc deficiency in soils is very common worldwide (ATSDR, 2005) while Zn is required in minute quantity by animals. Low concentration of Zn is essential for plant and animal life including human (Praveen, 2005). High values of Zinc in the aquatic environment affect the movements of fish in streams and may also have acute physiological effects on fish.

Kahatano *et al*. (1995) suggest that Zinc occurs in rocks as sphalerite (ZnS). High values of Zinc in the aquatic environment affect the movements of fish in streams and may also have acute physiological effects on fish. Skidmore (1992), demonstrated that acute exposure of *rainbow trout* to Zinc caused a severe inflammatory reaction in fish gills this was followed by circulatory breakdown, tissue destruction, respiratory collapse and death.

Copper (Cu)

Copper is found as mobile brochantite or copper sulphate. Near the soil surface, copper sulphide minerals oxidise and much of the metal goes into the solution (U.S.EPA, 2005a). The dissolved copper ions can then be carried down by groundwater. Copper adsorbs to most soil constituents more strongly than any other toxic metal except lead. It however, has a high affinity for soluble organic ligands, the formation of these complexes may greatly increase its mobility in soil at different temperatures (Garvey *et al*., 1991). Although copper in water is a hazard to many aquatic organisms, minute amounts of copper in the diet are needed for human, plant and animal enzymes (Garvey *et al*., 1991). Copper is not classifiable as human carcinogenicity. However it has negative effects to some plant species. At very low concentrations (10.2 µg/l), copper inhibits algal cultures and deficiency problems are rare in humans (U.S.EPA, 2005a). Permissible value of Cu in water and food as set by WHO 1998 is 1.0 mg/l.

Thus from the above explanation and examples of the effects of heavy metals on humans and aquatic environment (Bakir *et al*., 1996; George, 2001; Knight, 2000; Lawrence *et al*., 2004 and State of Texas, 2005) efforts to control sources of pollution and prevention of contamination in rivers and streams is needed as these metals exhibit a combined toxicity greater than that of the individual elements when they are left to accumulate this is the common situation in water polluted by heavy metals from mining. For example, laboratory tests by Eaton (1973) attained a lethal threshold for fat head minnows when a mixture of Cu, Cd and Zn was present at a concentration of 40$^{\%}$ of its individual lethal threshold.

2.3.3 Physicochemical parameters

- **pH**

pH is a measure of acidity and alkaline conditions of a solution or water. It is used to express the intensity of acidic or alkalinity of a water sample, which actually indicates the concentration of hydrogen ions present. It is influenced by temperature (Mason, 1993). For example, an environment with low pH has relatively high temperatures and vise versa. The acid mine drainage, discharge of effluents, acidic precipitation, runoff, microbial activities and decay process change the pH of water. Acid mine drainage affects pH resulting in reduced acid neutralizing capacity and lower pH. Low pH increases the solubility processes of heavy metal compounds, which increase contamination in the environment. Anderson *et al*. (2000) found that the degree of solubility determines the toxicity of the heavy metals and that they are more toxic at low pH of less than 4.5 because they are more mobile.

The RMPC (2006) recommended pH for drinking water ranges from 6.5 to 8.5. At pH values less than 7.0, corrosion of water pipes may occur, releasing metals into drinking water. This can be toxic and may pose health problems if concentrations of such metals exceed recommended limits (Anderson *et al*., 2000). The significance of pH includes changes that occur when wastewater is discharged into the environment. At pH values between 6.7 and 8.6 for instance aquatic environments are well balanced (WHO, 1998). However, at pH less than 5 or more than 9, most aquatic species are affected. The pH varies with the amount of dissolved materials in the water.

Studies in Norway and Sweden indicated extinction of fish populations often resulted from chronic reproductive failure because of acidification induced effects on sensitive developmental stages (Brungs *et al*., 1998). Acid stress (pH 4.0-5.0) also has caused fish mortality by interfering with the physiological mechanisms regulating active ion exchange across gill membranes (Brungs *et al*., 1998).

- **Temperature**

According to Lakudzala *et al*. (2004) temperature is a measurement of intensity of heat stored in a volume of water; that is the degree of hotness or coldness of water. The natural source of heat is solar radiation. Surface water temperatures naturally range from 0°C under ice cover to 40°C or more in hot springs, while groundwater temperatures range from 4^{o}C to 15°C (Lakudzala *et al*., 2004). The direct effect of temperature as an environmental factor is difficult to assess because in the stream or river, it is often linked with the speed of the current and the type of bed. Cooler waters are usually associated with shallow rapid and more common in the upper reaches of rivers.

Temperature also influences the conductivity of charged particles dissolved in water and their mobility. Higher temperature values lead to higher conductivity values. Lakudzala *et al*. (2004) suggests that all reactions, chemical and biological, in water are affected by temperature. The higher the temperature values the warmer the water and the higher the conductivity values with the temperature increase of about 1.9°C which influences drinking water quality. WHO (1998) recommends the temperatures of 12°C to 25°C as the standard for drinking water. A recommended upper limit is 32°C. Aquatic organisms such as fish species, *trout* for instance can die with increase in temperature beyond 32°C.

- **Electrical conductivity (EC)**

According to Stednick (1991) the conductivity of water depends on the quantity of dissolved salts present and for dilute solutions it is approximate proportional to the total dissolved solid (TDS) content. The presence of dissolved salts in water increases its electrical conductivity, which varies according to the temperature. Drinking water has a conductivity ranging between 50 and 500 µS/cm. Domestic water has conductivities above 1000 µS/cm. The recommended limit of conductivity for water required for direct abstraction to supply is 400 µS/cm (RMPC, 2006). Conductivity depends upon the number of ions or charged particles dissolved in water and their mobility. Water conductivity increases with increasing mobility of ions in water (Stednick, 1991). Conductivity and TDS are used to measure the water quality very high values of dissolved ionic matter are good indicator of possible water pollution sites. Industrial discharges, mine waste, sewage and agricultural runoff for instance can raise conductivity of surface and groundwater (WHO, 1998).

- **Sulphates (SO_4^{2+})**

According to Berner and Berner (1996) the most significant source of sulphate in water is from the weathering of rocks. The main sources include the Iron sulphide (FeS_2, FeAsS), Calcium sulphate as gypsum ($CaSO_4.H_2O$) and anhydrite ($CaSO_4$). Sulphates residue may also result from the natural or artificial precipitation of sulphur bearing waste from a variety of chemical wastes such as sulphur dyes (Nemerous and Avijit, 1991). Sulphate generates toxic acids such as sulphuric acid, vapours or fumes in dangerous quantities when exposed to pH conditions below 5 and this can have serious implication for the survival of fish eggs, their fry and benthic invertebrates (Nemerous and Avijit, 1991). During this process a particular group of bacteria referred to collectively as the "*sulphate oxidising bacteria*" (SOB's) play a role in increasing the rate at which the chemical reactions take place as shown in Equation 1.

$$4\,FeS_2 + 15\,O_2 + 14\,H_2O \rightarrow 4\,Fe(OH)_3^{-} + 8\,H_2SO_4 \qquad (1)$$

Pyrite + Oxygen + Water → Ferric Hydroxide + Sulphuric Acid

A study carried out by Haraguchi (2005) in Indonesia on the effect of sulphate discharge on river water chemistry from peat swamp forests found that water discharged from canals after pyrite oxidation into the main stream of the Sebangau River and Kahayan River showed lower pH compared to the mainstream water of the rivers, implying sulphuric acid loading from the canal to the main stream of the rivers causes not only acidification of soil and water but also acidification of the limnological ecosystem.

- **Nitrate (NO_3^-)**

Nitrate (NO_3^-) is essential to crops but harmful to humans and animals if taken in high doses (Wetlands, 1999). Nitrates are naturally occurring substances that are vital for plant growth. Nitrates are component of animal manures and artificial fertilizers. They are highly soluble and easily washed away from fields which often contains large amounts of nitrate nitrogen (NO_3^-) to rivers, where eutrophication may result (Hoko, 2007). It may also percolate through the soil to ground sources of water supplies where they cause contamination to dangerous levels. Nitrate itself is of low toxicity and once absorbed into the blood stream is rapidly excreted in urine or faeces and recycled in the saliva (Wetlands, 1999). Nitrate in gold mines comes from blasting processes, which use explosives that normally contain nitrogen compounds. Common examples of such blasting agents are ammonium nitrate and fuel oil (ANFO), water gels and nitroglycerin explosives. During blasting these gaseous compounds from the explosives are released to the mine wastes and the surrounding environment (Orem, 2005).

It can be concluded that the knowledge of the physicochemical parameters and their effects as pointed out by (Brungs *et al*., 1998; Wetlands, 1999; Anderson *et al*., 2000; Lakudzala *et al*., 2004; Haraguchi, 2005; Hoko, 2007) in water is important for authorities to take proper action in preventing pollution to the environment and for the good health of the people, it is also encouraged to regularly test effluents from mining, wastewater and rivers water quality.

2.4 Mitigation of toxic pollutants

Mitigation refers to the reduction of the toxic pollutant in sources such as soil and water (Truong and Claridge, 2004). The awareness of the detrimental effects of heavy metals in the environment, their bioaccumulation, biomagnifications through food chain combined with their non biodegradability is responsible for setting up mitigation and remediation policies. Truong and Claridge (2004) summarized mitigatory measures/strategies that include; avoidance of dumping wastes in water bodies and setting specific regulation guidelines limits for heavy metals concentration in safe water and soil for biota, example, limits for Cd is 0.003, Cu is 1, Pb is 0.05 and Zn is 3 mg/l for drinking water quality according to WHO (1998) guidelines, containment of mining wastes and tailings in special settling ponds and dams, immobilizing the wastes into specified confinement pile areas, proper mining waste management by setting treatment standards before disposal, delaying or stopping miners or companies mining projects until they meet regulations by conducting Environmental Impact Assessment (EIAs) before project commence.

Vernet (1999) however, grouped remedial techniques for toxic heavy metals removal into two categories namely; destructive and recovery methods. In destructive methods, the heavy metal is precipitated either as a heavy metal hydroxide, carbonate or sulphide and disposed as sludge. Although this is a simple and inexpensive method, when employed for industrial wastes, it fails to produce effluent of required quality due to the formation of more soluble metal species (Tare and Venkobachar, 1995). The pH has to be raised to above 7 to precipitate heavy metals held in solution (Nyer, 1985). Recovery by chemical or physical methods such as electrolytic and evaporative methods is possible when metal concentrations are more than 1g/l. Development in environmental biotechnology have helped in identification of biosorbents with high affinity for inorganic and organic pollutants (Tsezos and Keller, 1993). The living as well as dead microbial biomass can decontaminate the effluents of wastes from mining and refining industries. For example, *Rhizopus arrhizus*, a by-product of industrial fermentation, has 2 to 5 times higher uranium uptake capacity of 180 mg (Tsezos and Keller, 1993).

Muzzarelli *et al*. (1982) also reported that *Asparilligus niger* from citric acid fermentation industry can remove a wide variety of heavy metals. Gomez *et al*. (1989) argues that the removal of Cu and Cd in soil and water can be achieved by the use of sodium borohydride chemical reduction. This was demonstrated in Blue Mountain at Palmerton, USA where over 800 ha of forest vegetation died due to the emission of Zn, Cd, Pb, and SO_2 from Zinc smelter (Sopper, 1998). Fly ash lime was applied to the contaminated soils and water to promote soil neutralization. In the presence of moisture, lime undergoes hydrolysis of the CaO and MgO through ion exchange under alkaline conditions. This demonstrates that soil pH plays an important role in precipitating heavy metals to avoid bioaccumulation in biota (Ernst, 2000). Expensive methods, such as ex-situ soil washing using chelating agents such as EDTA have been used (Woodbury, 1992). Recently a biodegradable alternative ethylenediamine disuccinic acid (EDDS) has been proposed in Switzerland to treat Cu, Pb and Zn contaminated water and soils (Truong and Claridge, 2004).

In summary, it can be said that mining activities represents interrelated social, health, safety and environment issues. Therefore, pollution prevention measures at the source need to be considered for effective water quality management. Among other methods could be pretreatment of effluents prior to disposal, precipitation to reduce metal contents by treating using lime and treatment of acid mine water by sulphate reducing bacteria (Christensen *et al*., 1996).

CHAPTER THREE

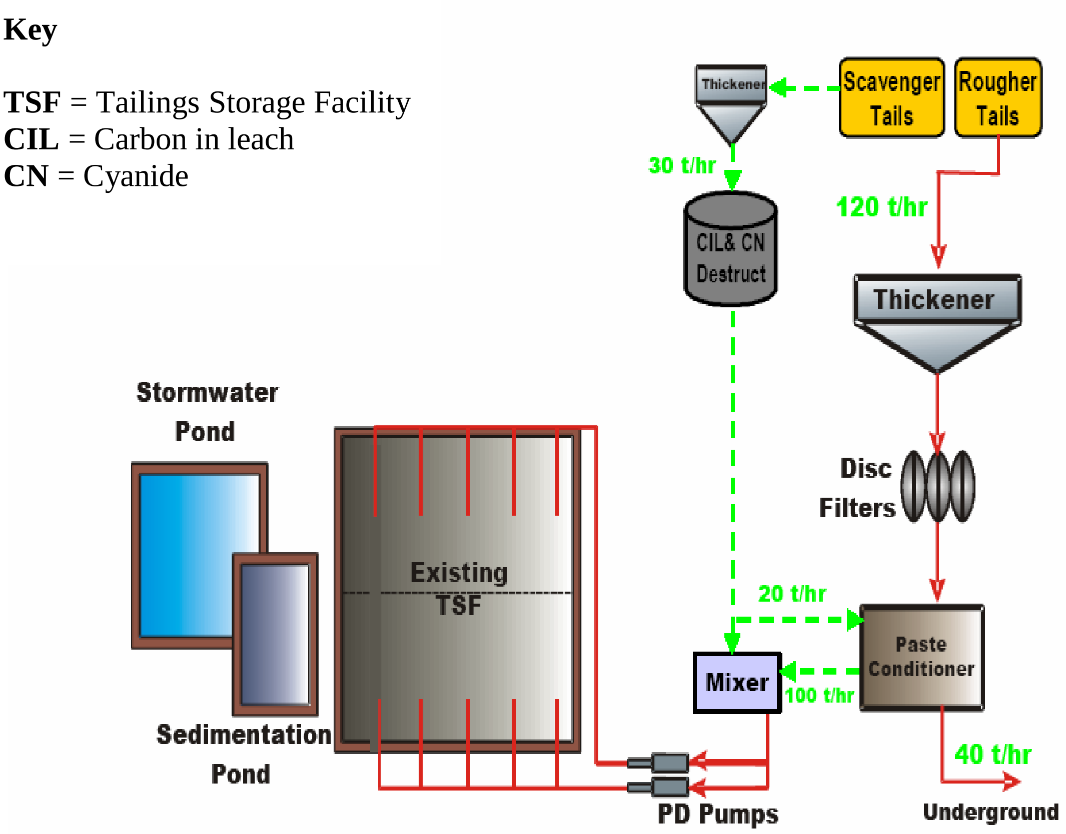
3. STUDY AREA

3.1 Location and Operation

Bulyanhulu Gold Mining (BGM) is an underground mine located approximately 45 km South of Lake Victoria (Fig.2) at an elevation of 1,200 metres above Sea Level. It is located 75 km from Kahama District in Shinyanga region. Construction of the project commenced in 1999 and the mine was commissioned in March 2001. The estimated life expectancy of the mine is approximately 25 years.

Fig.2. Map of Tanzania showing Bulyanhulu Gold Mine Location (Source: BGM, 2008)

BGM comprises underground mining and mineral processing operations contained within a 1.4 km^2 fenced area including; underground mine, processing plant, paste backfill plant, tailings cell, waste rock dumps and associated Effluent Control Ponds, The mine also has 48 km water supply pipeline from Lake Victoria. The gold processing plant at BGM is designed to process an average of 2,500 dry tonnes of gold bearing ore per day. The plant operates on a 24 hours per day, 365 days per year basis. Ore feeding the process plant contains gold, silver and copper. The feed to the plant contains 11 to 14 grams per tonne gold and around 0.5$^{\%}$ copper (Shuttle, 2005).The mine produces gold and copper via gravitation and flotation circuits and utilizes third party refineries for gold-copper concentration. Fig.3 shows the schematic layout of general process flow. The extraction of the gold bearing rocks (ore) is carried out through the use of underground mining methods after which it is hoisted to the surface for processing. The ore is then crushed to produce a slurry that is then classified to separate fine and coarse particles. The finer fraction is then fed into the flotation circuit for further processing, the coarse fraction is sent to the gravity concentration circuit. The gravity circuit recovers gold through the use of shaking tables to recover coarse free gold, drying and smelting to produce gold and silver. The material fed through the flotation and dewatering circuit is processed further to produce copper concentrate and tailings (Shuttle 2005).



Key

TSF = Tailings Storage Facility
CIL = Carbon in leach
CN = Cyanide

Fig.3. Schematic layout of general gold process flow at Bulyanhulu Gold Mine (Source: Shuttle, 2005)

3.2 Geology and Topography of the Study Area

The Bulyanhulu area is essentially flat and has few rock exposures other than occasional granitic hills at over 6 km distant from the site. The area is typically represented by extensive lateritic and saprolitic weathering profiles that have been developed to a depth of between 50 to 80 m (Norecol and Moore, 1997). Lithostratigraphy has been obtained almost exclusively from diamond drill cores. The gold, silver, and copper mineralisation at Bulyanhulu occurs in mineralised “reefs” (discrete semi-parallel zones) striking 315° and dipping steeply to the northeast. The surface geology of the project site is relatively simple, comprising an upper zone of transported soils overlying residual soils. In areas of high ground, the upper transported unit comprises slightly clayey, silty sands and organic topsoil, and is typically less than 1m thick.

3.3 Climate

The mine maintains a weather station at Bulyanhulu. The weather station is equipped of recording temperature, rainfall, wind speed, wind direction, atmospheric pressure, sunshine hours, and evaporation. There is available data for weather in the area since July 1999, when the station was installed. Meteorological data for all parameters is collected and stored within the weather station’s data logger. An automatic data retrieval system was introduced in January 2005 and is operated on a daily basis. The rainfall recorded for the period of 2006 was 1030 mm with 49.50 mm the highest rainfall recorded in a 24hr period on the 16th of December 2006. The annual rainfall, temperature, humidity and evaporation at Bulyanhulu Gold Mine as recorded at the weather station in 2004 is shown in Appendix 1 and 2. The temperature within the mine area indicate a uniformity of both temperature extremes and monthly mean readings with the mean monthly temperatures ranging from 21°C in July to a high of 25 °C in February. The range of temperatures in the area is consistent with those within the Shinyanga region which reflect a subtropical climate.

3.4 Drainage

As stated previously the mine concession area is confined to the Lake Victoria basin on a relatively higher ground between Bulyanhulu River to the north, and the Kabhanda River to the far East. The Bulyanhulu River has two primary tributaries, the Bujula and Butobela, which originate in a seasonal wetland to the North, and from surface runoff to the West, respectively. The Bulyanhulu River flows eastward for approximately 15 km to join the Kabhanda River (Norecol and Moore, 1997). The river is henceforth known as the Nyakadohomi, which flows in a northeasterly direction for approximately 50 km, before joining the Isanga River, which also flows into Lake Victoria at Smith sound. Most of the rivers in the area have water during the rain season and are dry for most of the year (July to October). However, the Bulyanhulu River has water flowing throughout the year, although the flow is intermittent at the peak of the dry season.

The river downstream of the mine is used for irrigation of crops (mainly vegetables and maize), and for domestic use, including drinking without treatment. The river channels in the region are poorly defined, being shallow and wide, often merging into broad floodplains. The streambeds are composed of fine textured alluvium, which lack stability and allow the river channel to migrate between opposing banks during times of intermediate flow. Sediment loads are generally high, due to the nature of the erodable soils and the amount of human induced soil disturbance in the region from agriculture and artisanal miners (Norecol and Moore, 1997). The ephemeral nature of the Bulyanhulu River is a limiting factor in its potential to support commercial fish populations. Compounding this problem are high sediment loads in the water column and siltation of the streambed, which reduce primary productivity, food sources, and the availability of spawning and rearing habitats. Fish species that are present in the river have developed physical adaptations or behavioural patterns to live in the seasonally harsh conditions (Norecol and Moore, 1997). Local fish capture is of a subsistence nature. There is no official information available regarding the catch data of subsistence fisheries, as efforts to document fish presence and distribution in Tanzania have been focused on major commercial fisheries (Norecol and Moore, 1997).

3.5 Socioeconomic activities

The socio-economic situation in the study area is closely linked with the mining activities which have occurred for more than 30 years. Mining activities in the Bulyanhulu area started in the 1970s. Activities at that time were dominated by artisanal miners. The number of people involved in the mining was small, and the influx of people into the area was low. Currently, gold mining activities in the vicinity of BGM are conducted by both large and small scale miners. Stamico, Kakola, and Bariadi are among villages that represent artisanal mining workings around the BGM project. However, the most common activities in the area are agriculture and livestock. Other activities of lesser importance include timbering, charcoal making, and gardening. Mining, which became prominent in the late 1970s, is carried out by migrants usually at a small scale and unauthorized level.

CHAPTER FOUR

4. MATERIALS AND METHODS

4.1 Study design

According to Schimitz (1995), prior to the sampling of the affected area, sampling operations need to be broken down into four components namely; selection of sampling stations, selection of water quality parameters, sampling frequency, collection and analysis methods. The study aimed at assessing the potential impact of pollutant levels on the Bulyanhulu River, Effluent Control Ponds, local boreholes and shallow wells. The on-river sample points were identified as W1 through W4, SW1 and SW2 (community shallow wells), Waste dump runoff water pond (WDRP) and Tailings dam reclaim water pond (TDRP) as Effluent Control Ponds as well as Plant site monitoring borehole (PMB2) and Tailings dam monitoring borehole (TMB8). The layout of the area and the sample collection points are shown in Figs. 4 and 5. Ten sampling campaign were accomplished during wet season from January to March 2008 at regular intervals of one week. However, it is necessary to collect data over four seasons to establish the effect of seasonality on the quantitative data collected.

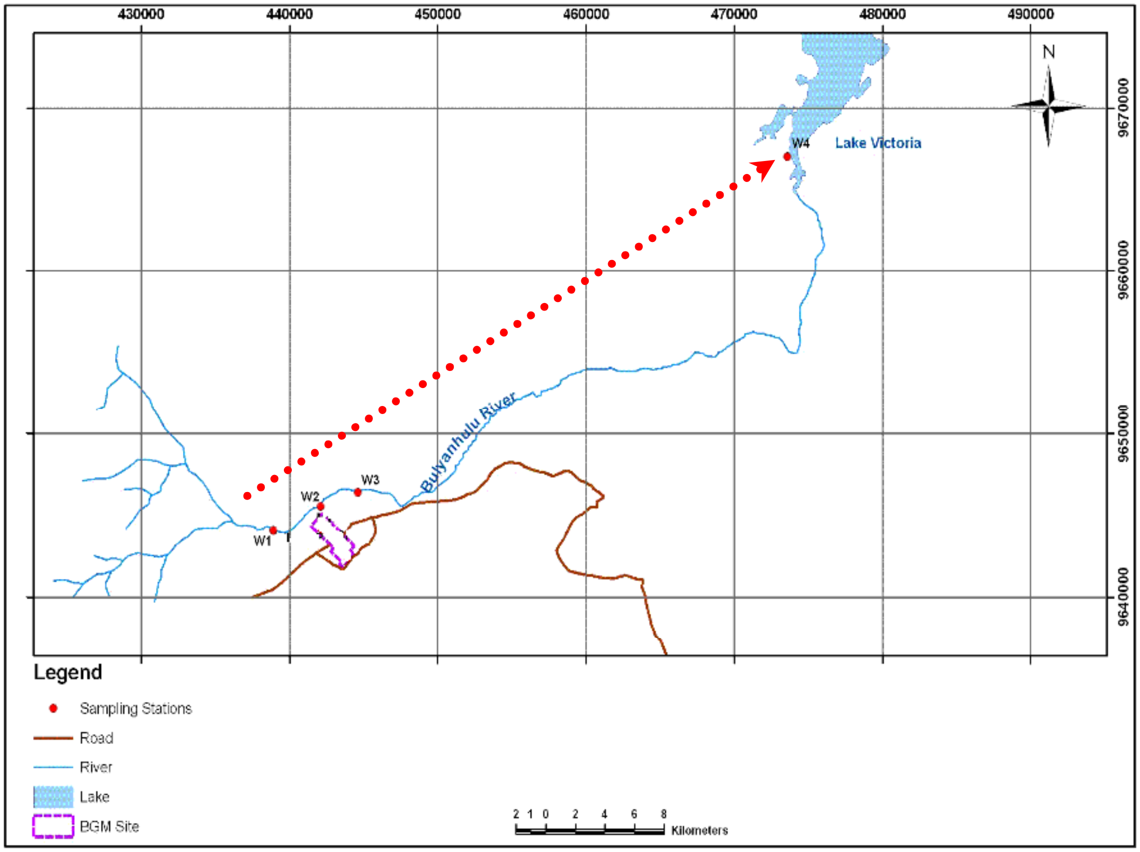


Fig.4. Study design: Showing the position of the mine and Bulyanhulu River sampling points.

4.1.1 Selection of sampling points

The sampling points were selected after consideration of the WEGS report (2002) report, which indicates that the topography of BGM area generally drains in the direction of the Bulyanhulu River. Another reason was due to the sample points being very close to gold mining activities. Closeness of these sampling sites to the mining activities makes them susceptible to pollutants through leachates and seepage from mine effluent s. WDRP and TDRP are man made pollution control ponds. They are characteristically different in comparison to other surface water sampling points (flowing water). They are not in direct contact with the river in question only in the event of floods. The reason for monitoring them was to determine their influence on surface water quality of Bulyanhulu River and local groundwater quality, where by they could affect the water quality of (PMB2 and TMB8) through seepage and infiltration as some are not lined with any material.

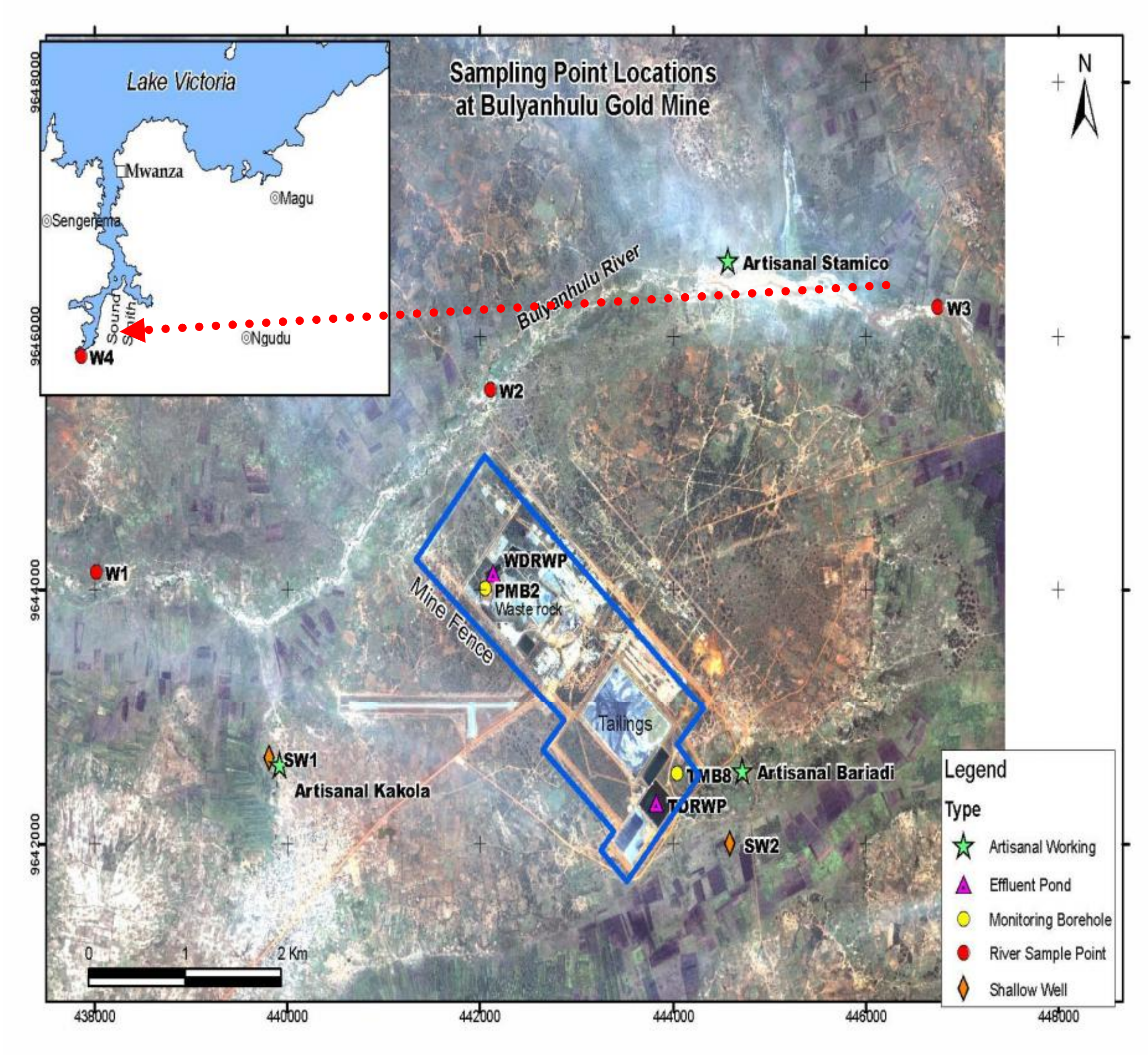


Fig.5. Map showing location of all sampling points.

Note: W1-W4 are river sampling points, WDRWP and TDRWP are mine effluent ponds, SW1 and SW2 are shallow wells, PMB2 and TMB8 are monitoring boreholes.

Grab water samples were collected at strategic sample points (Fig.5) along the Bulyanhulu River, community shallow wells, as well as at the two mine Effluent Control Ponds. These ponds were constructed to prevent runoff from tailings storage facility and waste rock dumps. In addition to surface water samples collection, groundwater samples were also collected 50-70 m adjacent to the Effluent Control Ponds and mine dumps to determine the influence of effluent ponds, tailings and waste rocks on the groundwater quality of boreholes. The water samples were collected from the existing boreholes in order to determine specific water quality parameter values.

4.1.2 Selection of parameters measured

The selection of monitoring parameters was based on their indicative characters (host rock type, processing method, ore type, commodities being mined and their hazardous characters as well as by taking into account the activities taking place in BGM vicinity. For instance, the ore body of BGM contains a high degree of sulphitic minerals (pyrite and chalcopyrites) and the mine operations use blasting materials such as ANFO, with Ammonium and Nitrate contents thus there was a need to monitor the concentration of these parameters.

The choice of water quality parameters was also based on the list by McBride (1994), which prioritise toxic parameters that might be influenced by gold mining activities and the subsequent increase or decrease may be detrimental to the biotic life (aquatic, fauna, flora and human health) in the local area. Studies on *brook trout* by Mc Kim and Benoit (1971), showed that water polluted by gold mining activities due to acid mine drainage (AMD) had concentrated heavy metals such as Hg, As, Fe, Ni, Zn, Cu and Pb. An Iron concentration of 0.3 mg/l had had effects on fish populations, and a Zinc concentration of 0.18 mg/l greatly reduced egg production of the *fathead minnow* (Mc Kim and Benoit, 1971). A study by Mount (1973) on *fathead minnows* (*Pimephales promelas*) showed that low pH values also affected behaviour and reproduction of aquatic organisms. The fish behaviour was abnormal and fish were deformed at pH levels of 4.5 to 5.2.

4.1.3 Time and frequency of sampling

Sampling locations were located to ensure samples collected were representative in space. Sampling frequency should also be such that the samples are representative in time. Table 3 presents the number of samples collected per site for the entire sampling campaign. Sampling was done in the mornings starting at 0900 a.m. at river points and shallow wells, then in the afternoon (1500 p.m.) at boreholes and Effluent Control Ponds.

Table 3: Number of samples collected per sample class for entire sampling campaigns.

Sample classes	*Number of sampling campaigns*	*Number of samples collected in total per site*
Bulyanhulu River	10	40
Effluent Control Ponds	10	20
Residential shallow wells	9	18
Boreholes	9	18

4.2 Sample collection and analytical methods

4.2.1 Surface and groundwater sampling

Surface water samples were collected using 500ml black and white polyethylene plastic bottles. These containers were prepared by washing with soap and water, rinsing with tap water followed by distilled water. When sampling, river water samples were collected just below the water surface with the containers facing away from the direction of the flow. Sampling was also conducted by completely dipping sample bottles in the effluent ponds and shallow wells water. Fig.6 shows collection of water samples upstream the mine at W1 river point.

Fig.6. Collection of surface water sample upstream point (W1) of the Bulyanhulu River on 14th Jan 2008.

For groundwater samples bottles with a small amount of water collected flushed out two times before collecting the sample this was done to obtain the representative samples of the aquifer around the borehole and reduce possibility of sample contamination as suggested by (Schimitz, 1995). The sample bottles were first rinsed with water to be sampled before they were filled with water. Sampling bottles were labeled soon after sampling process. Precautions were observed to minimize sample contamination and decomposition.

4.2.2 Sample transportation and storage

After the sample collection the bottles were labelled according to sample point identification name (e.g. W1), dates and sampling time then transported to the laboratory in a cooler box with ice. In the laboratory samples were stored in the refrigerator at <4 °C until analysis, which was carried out within 24 hours for all parameters. According to Kilian (1997), water samples must be analysed immediately or stored in a container with a preservative (where applicable) to maintain the integrity of the sample.

4.2.3 Physico-chemical parameters and heavy metals analysis

Water quality parameters and the methods utilized in this study are presented in Table 4. Parameters measured in the field and in the laboratory were temperature, pH and conductivity. They were measured in the laboratory by employing the HACH spectrometer equipment (2001) standard procedures and an automatic pH – meter with a Temperature, conductivity and pH probe in the field. The UV-Vis Spectrometer was used for the analysis of (SO_4^{2+}) and Nitrate (NO_3^-). Cyanide (CN^-) was analysed by using HACH DR 4000V Spectrophotometer according to APHA (2000).

Table 4: Parameters measured in the study area for the sampling period of 14th Jan to 17th March 2008.

Parameters	*Units*	*Method used*
pH, Temp and EC	pH unit, °C and μS/cm respectively	Automatic pH – Meter and HACH (2001) with a temp, conductivity and pH probes
Metals: Hg, As, Fe, Ni, Zn and Ag	mg/l	Inductively Coupled Plasma Spectrometer
CN^-	mg/l	HACH DR 4000V Spectrophotometer
SO_4^{2+} and NO_3^-	mg/l	UV-Vis Spectrometer

The analysis of water samples for heavy metals at various sampling points employed the standard water quality analysis techniques used at the BGM analytical laboratory in accordance to standard method. The preparation of the stock and standard solutions for the heavy metals parameters (Hg, Cu, Ni, Fe, Zn and Ag) were filtered through Whatmann 40 micron filter paper and the filtrate collected in a conical flask. The analysis was done by using Inductively Coupled Plasma-Optical Emission Spectrometer according to APHA (2000). This elemental analysis method can be successfully used to determine the elemental composition of different samples from environment like surface water (Boumans, 1997).

Microsoft Excel (2003) was used for statistical data analyses to obtain standard deviations for each parameter measured for the whole sampling period per sampling point. Descriptive statistics were used to describe, organize and summarize the data in the form of tables and graphs.

4.2.4 Quantification of pollutant loads in river and effluent pond sampling points

According to Riza (2000), the estimates of pollution loads are based on water quality monitoring data (concentration of pollutants) and hydrological data (e.g. river discharge).

$PL = QC$ ………………………………………………………………………………….. (2)

$PTL = Q(C_1 + C_2 + C_3 + ... + Cn)$ ………………………………………………………… (3)

$Q_m * C_m = Q_R C_R + Q_P C_P$ ……………………………………………..(4)

The potential loads (kg/day) of each pollutant were calculated using Equation 2 and Equation 3 for points with insignificant change in flow. The indicative potential pollution in the river was determined following the mass balance equation as suggested by Cho *et al*. (1991), using Equation 4 to determine the concentration mix in (kg/m ^{3}) of pollutants in both river and waste dump effluent pond (WDRP).

In the equations above Q is the flow rate (m ^{3}/day) and C in this study was the average concentration of pollutant (kg/m^3) for each pollutant for the entire sampling period. The flow mix of both river and effluent pond is presented as Q_m and C_m is the pollution concentration mix of river and WDRP. The subscripts C_R, C_P $Q_{R,}$ and Q_p represent average concentration in river points, mean concentration in WDRP, river flow rate and WDRP flow rate respectively.

4.2.5 Mapping spatial distribution of pollutants among sampling classes.

Spatial distributions of the concentrations of the principal heavy metals and non metallic constituents (Ni, Zn, Fe, SO_4^{2+}, EC, and pH) were deduced using the Golden Software Surfer version 8. This was used to plot digital elevation models (DEM) to investigate the trend of surface concentrations of elements in relation to their geographical positions by using GPS coordinates.

4.2.6 A review of BGM monitoring program

A review of BGM monitoring programme was done by collecting relevant information and data, data analysis and by reviewing existing documents such as reports and Acts.

4.3 Quality assurance and quality control

Quality-assurance and quality-control (QA/QC) practices were done for all phases of data collection and analysis in the field, laboratory, and during data validation. Field and laboratory protocols were followed to ensure that everything was done according to standard methods. In the field, 5 percent of the water-quality samples collected was field blanks. Sampling equipment at the field site was properly checked to detect contamination in sample collection, handling, and shipping. In the laboratory , equipment and supplies were regularly checked to ensure proper performance

4.4 Limitations of the analysis

The analysis of water samples gave results of the amount of dissolved metal in water. No account was made to test for different species of metals (total) . For a better understanding of the chemistry of metals at the study site, it is necessary to test for the different species. Moreover, the study was carried out during rainy season, which made sampling very difficult due to inaccessible roads and heavy rains. The amount of precipitation may also have had a direct positive effect on water quality and quantity at different sampling points. The recharge could therefore, resulted in an increase of the flow and contributed to a marked decrease of chemical element concentrations. The decrease of element concentrations indicates a marked dilution.

CHAPTER FIVE

5. RESULTS AND DISCUSSION

The background concentrations for surface water quality (Bulyanhulu River) were established by analysing water samples from Bulyanhulu River station one (W1) located 4 km upstream and West of the mining area. The point was used to find the water quality before the influence of Bulyanhulu Gold Mine (BGM) activities. On the other hand, the background concentrations for groundwater samples (boreholes) were established by using baseline data collected in Jan-Mar 2001 before initiation of BGM mining operation.

5. 1 Surface and groundwater results.

Prior to analysing surface and groundwater results an identification of the sources of potential pollutants emanating from BGM activities was done on site. The sources of pollutants identified were; gold process plant which combine the following processes; milling, thickening and liming of finally milled rock into slurry, pre-leaching of slurry using liquid NaCN and Oxygen, flotation of pyrites and gold using $CuSO_4$ activator, frother and aeropromotor collector. Other pollutant sources were the tailing storage facility, effluent control ponds and waste rock dump.

5.1.1 Bulyanhulu River

The results presented in this section are based on the individual statistical results of non-metallic constituents and heavy metals studied at each sampling point as shown in Table 5 and Table 6, which give summary of the ranges, averages, and standard deviations for ten sampling campaigns. Figs.7-13 presents the principal heavy metals and non metallic components and their variation among river sampling points compared to Tanzania Mining regulations of 2006 for receiving water (potable/groundwater) maximum permissible concentration RMPC (2006) and World health organisation WHO (1998) guidelines for drinking water quality.

Table 5: Bulyanhulu River analysis results (non-metallic constituents) for ten sampling campaigns (Jan to Mar 2008).

Sampling points	*pH*	*EC (μS/cm)*	*NO_3^- (mg/l)*	*SO_4^{2+} (mg/l)*	*CN^- (mg/l)*
W1	7-7.3 (7.2 ± 0.1)	180-320 (246 ± 41)	0.9-9 (4.6 ± 2.2)	48-65 (49 ± 13)	<0.005
W2	7-7.3 (7.2 ± 0.1)	150-270 (202 ± 37)	1.8-8 (4.9 ± 2.2)	49-99 (69 ± 16)	<0.005
W3	7-7.3 (7.1 ± 0.1)	80-250 (176 ± 56)	3-8.7 (5.3 ± 2.2)	16-165 (80 ± 46)	<0.005
W4	6.5-7.1 (6.7 ± 0.2)	189-220 (202 ± 9)	2-3.9 (2.9 ± 0.8)	<0.005	<0.005

Note:

- The range, average and standard deviation is based on 10 values for ten sampling campaigns.
- EC = Electrical Conductivity, NO_3^- = Nitrate-nitrogen, SO_4^{2+} = Sulphate and CN^- = Cyanide.

Table 6: Bulyanhulu River analysis results (heavy metals) for ten sampling campaigns (Jan to Mar 2008).

Sampling points	*Ag*	*As*	*Fe*	*Hg*	*Ni*	*Zn*
	mg/l	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*
W1	<0.005	<0.005	2.5-3.9 (3.2 ± 0.5)	<0.005	0.2-0.7 (0.4 ± 0.2)	0.8-1.6 (1.3 ± 0.2)
W2	<0.005	<0.005	2.2-4.9 (3.5 ± 0.7)	<0.005	0.2-0.9 (0.6 ± 0.3)	1.8-3.2 (2.7 ± 0.4)
W3	<0.005	<0.005	1.6-7.2 (4.7 ± 1.6)	<0.005	0.3-0.7 (0.5 ± 0.1)	0.4-3.7 (1.6 ± 1.0)
W4	0.1-0.1	<0.005	0.1-1.3 (0.7 ± 0.3)	<0.005	0.0-0.6 (0.1 ± 0.2)	1.2-3.6 (2.0 ± 0.7)

Note:

- The range, average and standard deviation is based on 10 values for ten sampling campaigns.
- Ag = Silver, As = Arsenic, Fe = Iron, Hg =Mercury, Ni = Nickel and Zn = Zinc.
- W1=1st point upstream the mine, W2= 2nd point close to mine site about 600m downstream, W3 = 3rd point 6km downstream from the mine and W4 = further downstream 40 km from the mine.

- **pH levels of river sampling points**

The pH values at all points in the river were found to be in the range of 6.5 to 7.3 throughout the entire sampling period and this is shown in Fig.7. All readings were close to those of the point upstream of the mine and lay within 6.5 to 8.5 pH values recommended by the Tanzanian guidelines for drinking water quality of 2006. WHO does not specify a guideline value for pH.

Water with low pH value <4.0 is acidic. It could also be soft and corrosive (Anderson *et al*., 2000). The river samples from where aquatic life is expected are within pH ranges of 6.5 to 8.7 (EPA, 1996). Despite the pH range being neutral, throughout the river at the time of study, there were few species visually observed into the river, the species diversity on aquatic species in the study area was not studied. Norecol and Moore (1997) suggests that species present in Bulyanhulu River have developed physical adaptations to live in the seasonally harsh conditions due to the high sediment loads in the water column. Some of the potential damages to aquatic biota from acid pollution are: increases in abnormal behaviors and reduction in reproductive capacity of adult.

Water with low pH can also cause premature damage to metal piping and has been associated with aesthetic problems such as metallic or sour taste (Anderson *et al*., 2000). Therefore water could leach metal ions such as Fe and Zn from the plumbing fixtures and piping because at low pH. Below a pH of 4 the solubility process of heavy metal compounds increases and therefore the degree of solubility determines the toxicity of heavy metals.

The overall results for pH indicated that, the river water was within the acceptable range of pH values and therefore, the river did not seem to be affected by mining activities with respect to pH at the time the study was conducted.

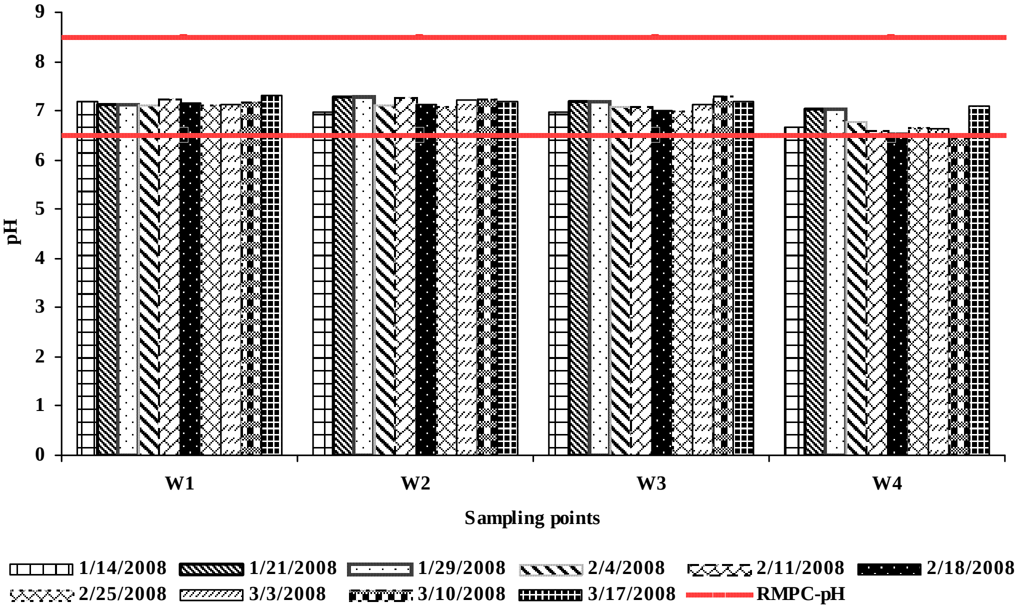


Fig.7. Variations of pH levels among river water sampling points.

Note:

- RMPC = receiving water (potable/groundwater) maximum permissible concentration guideline
- W1-W4 = river points.

- **Electrical Conductivity levels of river sampling points**

Conductivity values ranged from 80 to 320 µS/cm in river water samples as indicated in Fig.8 and Table 5. Generally all river water results were found to be within the Tanzanian recommended values for drinking water quality, this being 400µS/cm. However, the point upstream the mine was found to have higher levels of conductivity than the rest of sampling points, which was not expected. This could be attributed to high mineral salt concentrations which come from the dissolution of minerals in the soil. The presences of ions of inorganic compounds make the water exhibit high conductivities (Stednick, 1991).

According to Stednick (1991), conductivity is a convenient, rapid method of estimating the amount of dissolved solids present in water. Conductivity depends upon the number of ions dissolved in water and on their mobility. The conductivity is related to TDS in that if they are high, the TDS will also be high. In natural waters a greater portion of TDS is ionic, water conductivity increases with increasing mobility of ions in water and thus it is a measure of water quality. Very high values of dissolved ionic matter are good indicators of metals and possible water pollution as suggested by WHO (1998). However, for this study the levels of conductivities in river did not provide significant indication of the presence of metals. Kirk (1984) argues that increased levels of dissolved solids result in a reduction of the concentration of dissolved oxygen in water, which causes death to aquatic species such as fish. The solids that settle to the bottom of the river cover the spawning grounds and inhibit propagation (Martin *et al*., 1996).

Results obtained in this study for EC indicated that the EC of river water samples were within the acceptable range of EC values. Consequently, mining activities did not seem to influence the river with regard to conductivity.

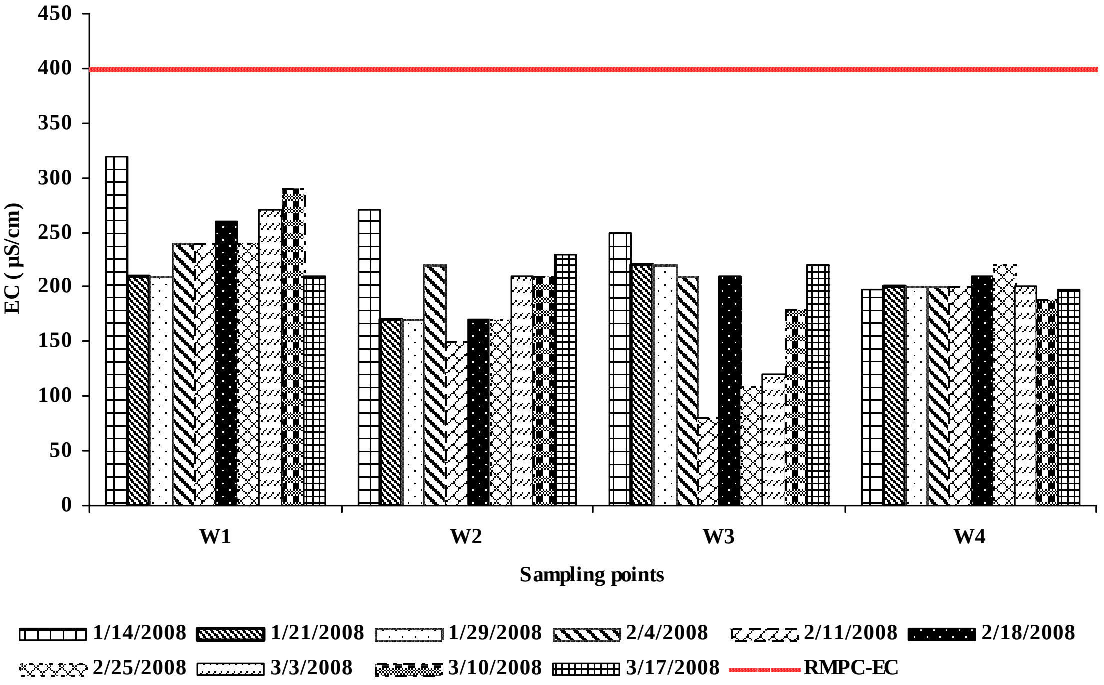


Fig.8. Variations of Conductivity levels among river water sampling points.

Note:

- RMPC = receiving water (potable/groundwater) maximum permissible concentration guideline .
- W1-W4 = river points.

- **Sulphate concentrations of river sampling points**

Sulphate concentrations for all river sampling points ranged from 0 to 165 mg/l as shown in Fig.9. All of river samples had sulphate concentrations below the Tanzanian and WHO maximum allowable limits for drinking water quality (600mg/l and 250mg/l respectively). Sulphate concentrations increased downstream from W1 to W3, with the exception of W4, which had measured concentrations below the method detection limit of <0.05 mg/l, this could be because of the natural purification of the river and dilution as this point is located on the shore of Smith sound on Lake Victoria that receives water from different sources as a result the water quality gets improved. Sulphate levels upstream the mines were likely due to recharge of surface water with acidic groundwater as a result of geological nature of the area. Points W2 (600 m from the mine) and W3, which is located 6 km downstream the mine, the sulphate could probably be linked to mining activities from effluent discharged into the river.

Sulphates occur predominantly in the form of simple SO_4^{2+} anions. According to Schmitz (1995), sulphuric acid is formed when air and water react with sulphur bearing minerals such as pyrite, commonly associated with gold mining. High sulphate concentrations are normally associated with low pH (Anderson *et al*., 2000). The resulting acidic condition kills aquatic animals and plants rendering the water unfit for use (Nemerous and Avijit, 1991). A study by Haraguchi (2005) found elevated sulphate levels in Sebangau and Kahayan Rivers in Indonesia, which resulted in a reduction of total abundance of fish and benthic invertebrate populations.

In conclusion, much of the river sampled points were not much affected by mining activities with regard to sulphate levels.

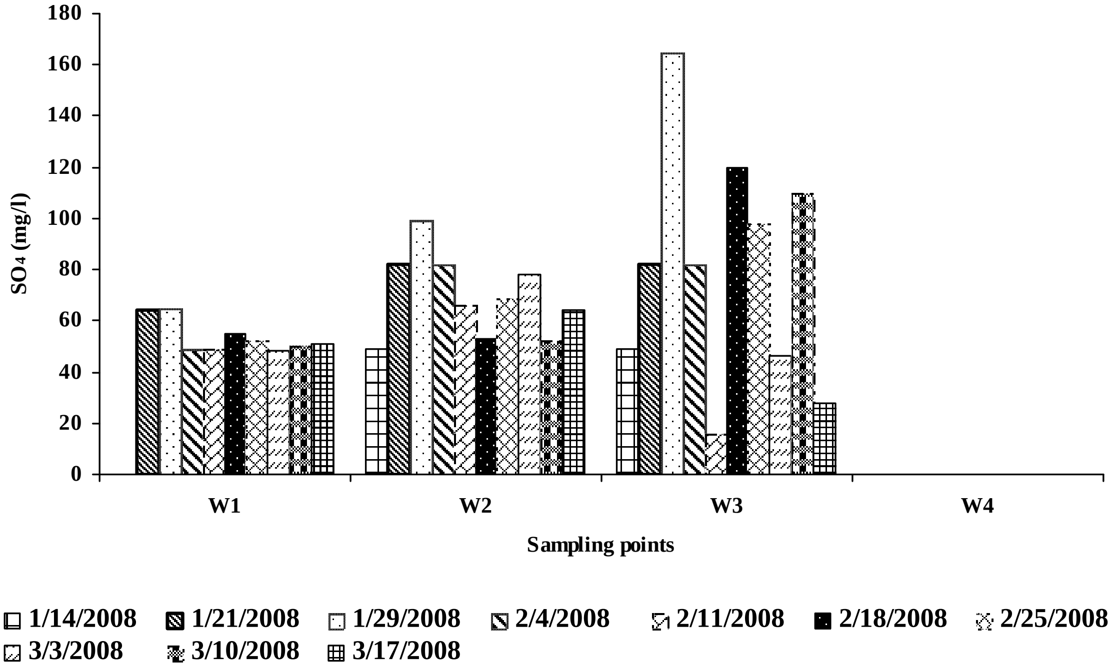


Fig.9. Variations of Sulphate concentrations among river water sampling points.

Note:

- RMPC = receiving water (potable/groundwater) maximum permissible concentration guideline (600 mg/l) and WHO = World Health Organization guidelines for drinking water (250 mg/l).
- W1-W4 = river points.

- **Iron concentrations of river sampling points**

The Iron concentration range was 0.1 to 7.2 mg/l in river water samples, as presented graphically in Fig.10. Of the total river water, only 20% of the number of all samples in all points met the 0.3 mg/l WHO guidelines limit and 1 mg/l Tanzanian guidelines for drinking water quality. This was measured at W4 point, which is located far downstream of the river on the shoreline of the Lake Victoria, low iron values could be as a result of self purification and dilution effects in the river as at this point the lake receives water from different tributaries. The results of iron showed increasing values from upstream to downstream the river at W1 to W3. High levels of iron at W2 and W3 could be linked to mining activities, as these points are downstream of the project area. Relatively high concentrations of iron were also measured upstream of the mine at river point (W1) and this could possibly be attributed to iron mineralization associated with the natural geology of gold mining areas, which constitute of pyrites and chalcopyrite (Kahatano *et al*., 1995; Ripley, 1996; Shuttle, 2005).

The literature review suggests that the higher proportions of dissolved metals such as iron are found in groundwater than in surface water because of the greater exposure of groundwater to soluble materials in geologic strata (Todd, 1959). High levels of heavy metals such as iron upstream of the mine could therefore be attributed to groundwater contamination plumes which can subsequently contaminate surface water via base flow (as noted by Keith *et al*., 2001). This can lead to the inference that the geologic condition of the area may contaminate the groundwater aquifer and subsequently contaminate surface water through base flow recharge.

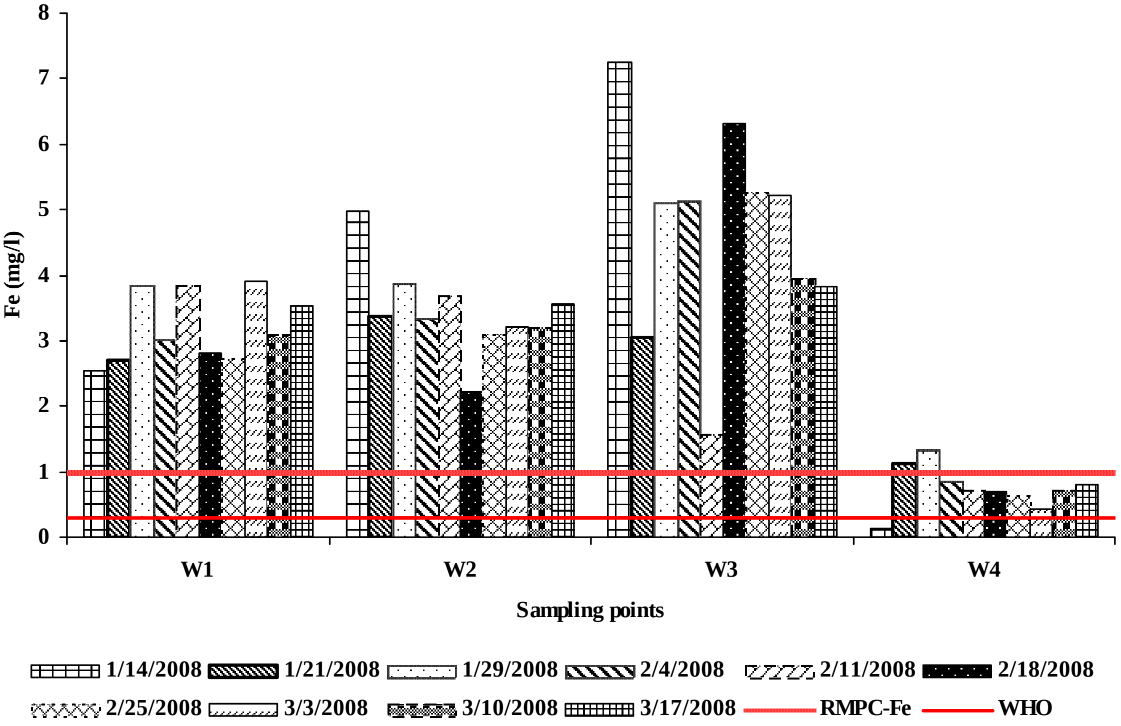


Fig.10. Variations of Iron concentrations among river water sampling points.

Note:

- RMPC = receiving water (potable/groundwater) maximum permissible concentration guideline and WHO = world health organization guideline.
- W1-W4 = river points.

According to Tolgyessy (1993), the forms in which dissolved and non-dissolved iron occur depend on pH and the presence of complex-forming inorganic and organic substances. In this study, the pH in all river sampling points ranged 6.5 to 7.3, indicating that water was around neutral conditions, the probable occurrence of iron at this range could be < 3 mg/l as suggested by Tarimo (2007) thus, low levels of iron were expected but this was not the case at some points during the sampling period.

The iron concentration standard associated with the aquatic life use is <0.3 mg/l (EPA, 1996). Most *mayfly nymphs* can not survive in streams with iron concentration below 0.3 mg/l. For example, Warnick (1989) found 0.3 mg/l of iron toxic to *mayflies, stoneflies* and *caddis flies*. Fish population however, can tolerate iron concentrations of up to 1.0 mg/l (Warnick, 1989). The potential survival of the fly species in the river is very minimal since most points at (97.5 %) of all the samples had shown very high (>0.3 mg/l) measured values for iron. In human iron concentrations above recommended values are associated with microbial growth, color, taste and brown staining precipitate (ATSDR, 2005).

In summary, the iron concentration at the various sampling points along the river were found to be high, the elevated values measured at river sampling points were attributed to anthropogenic sources (land use activities) with low inputs from mine activities at the project site. This was further substantiated where higher values of iron were also measured upstream the mine at W1 river point.

- **Nickel concentrations of river sampling points**

For all river sampling points Nickel concentrations ranged from 0 to 0.9 mg/l as shown on Fig.11. This exceeded the maximum nickel permissible level in water (Tanzanian and WHO guidelines of 0.05 mg/l and 0.02 mg/l respectively). About 82.5% of water samples collected at sample points on the river were very much higher than these threshold values for Nickel, the values increased from W1 upstream to downstream the river (W3). This could have been due to contribution from the mine for the points downstream the mine and land use activities such as artisinal mining since the river is within the mineralized area. This was also probably due to the geology of the area, which mainly constitute FeS and CuFeS. Frequently Ni ore occurs in sulphide form as NiS as pointed by Chimimba (1987) and this could explain why there were high levels of Ni in most river points. Low nickel levels were measured at W4 and this could be due to the effects of adsorption or dilution.

Nickel in mining areas is often associated with acid mine drainage, since the Nickel ore often occurs in sulphide form and is associated with other sulphide minerals (Lupankwa *et al*., 2004). Lawrence *et al*. (2004) reported negative effect of nickel on phototropic organisms such as *algae* and *cyanobacteria*. Human health effects of nickel include the disturbance of the respiratory system and asthma, birth defects, vomiting and damage to deoxyribonucleic acid at high concentration.

Therefore, it was concluded that high Nickel concentrations recorded for river points were due to the geological nature of the area, anthropogenic sources (land use activities and artisanals). These high Ni concentrations were not largely attributed to BGM mining activities, as the mine is still in its infancy stages (only seven years since operation).

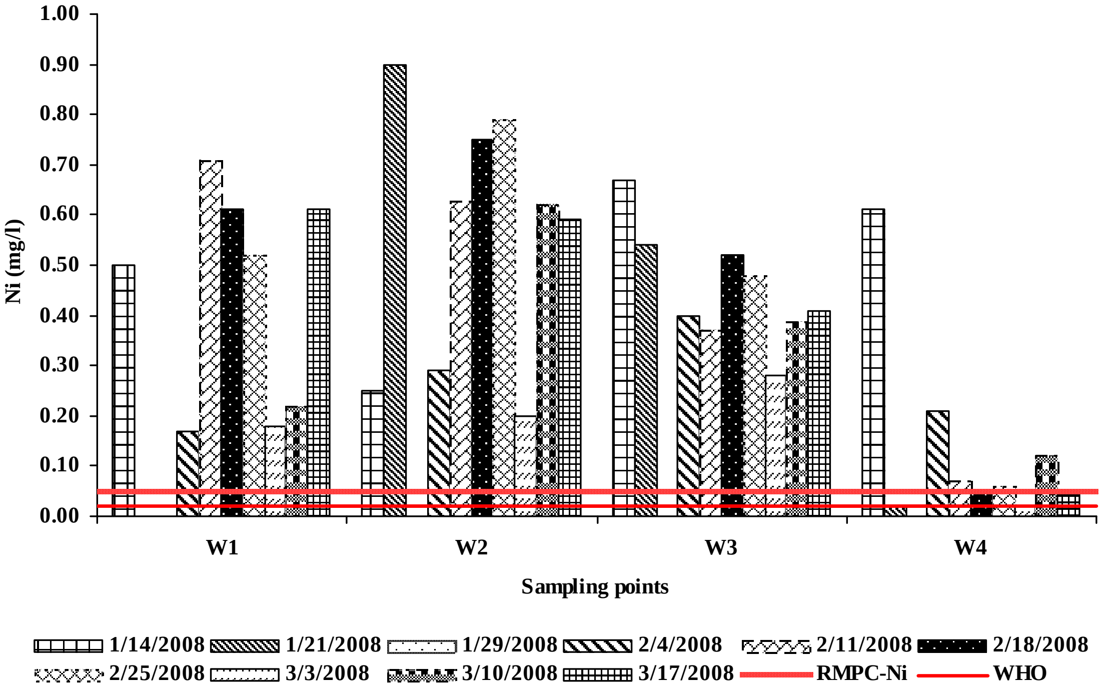


Fig.11. Variation of Nickel concentrations among river water sampling points.

Note:

- RMPC = receiving water (potable/groundwater) maximum permissible concentration guideline and WHO = world health organization guideline.
- W1-W4 = river points.

- **Zinc concentrations of river sampling points**

Zinc concentrations at sampling points along the river ranged between 0.8 to 3.7 mg/l as indicated in Fig.12. Values of Zn were all above the national acceptable levels of 0.2 mg/l but were within the 3.0 mg/l limit at most points when compared to WHO guidelines. The point upstream of the mine at W1 measured low values of Zinc compared to other points (downstream). High values of Zinc in the study area could be related to anthropogenic sources including mining activities, galvanized scraps, cast metal (Zn-Pb), brass (Zn-Cu), dry cells, vulcanized rubber and Zinc oxides (white pigment). This was also noted by (Kahatano *et al*., 1995) who found high levels of Zinc in streams and rivers of Lake Victoria Gold Fields.

Although the species diversity or impact of aquatic system was not studied it is important to note that the study found high levels of Zinc at all points downstream the river, which could affect the aquatic and human health that depend on the river and therefore, analysis should be conducted to find out how much the species diversity has been impacted. The impacts of Zinc on human health include fainting, nausea and stomach disorder.

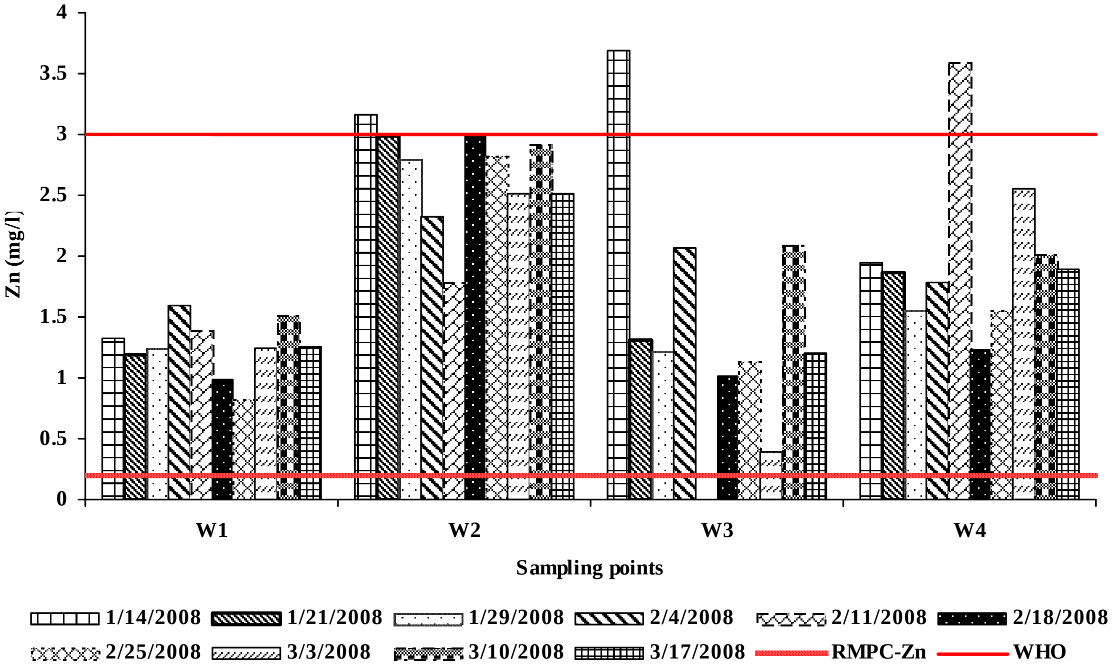


Fig.12. Variation of Zinc concentrations among river water sampling points.

Note:

- RMPC = receiving water (potable/groundwater) maximum permissible concentration guideline and WHO = world health organization guideline.
- W1-W4 = river points.

In summary, the river water was healthy with respect to Zn, when compared to WHO guidelines (1998) of drinking water quality. The reason for Zn being low probably was due to low inputs from mine or anthropogenic sources.

- **Other physicochemical and heavy metals**

The other physicochemical and heavy metals studied were Ag, Hg and CN^-. The concentration values of these elements were generally low in water. The levels of potential heavy metals Hg and CN^- were below the method detection limits of <0.005 mg/l by using Inductively Coupled Plasma-Optical Emission Spectrometer (ICP), the reason for these elements being low could be because the mine (BGM) was currently not using Hg as a method of extracting gold, Hg had been used by the artisanal miners around the Bulyanhulu River. Ikingura (1997) indicates that, the extent of pollution of both groundwater and surface water from sites close to artisanal amalgamation activities in Tanzania is still minimal no mercury concentration in excess of drinking water standards has been detected and this could explain why in the study site there were very low levels of Hg. For the case of Cyanide, the mine had started using cyanide for gold extraction from the scavenger tailings in July, 2007 after they had realised cleaner scavenger tailings contained a gold grade of 5% that could be recovered profitably. Hence the extent of pollution was not yet evident.

Concluding remarks for the river water quality results

From the discussion of the river water results it was demonstrated that pollution levels of heavy metals and non-metallic parameters of water in Bulyanhulu River varied from the water quality guidelines of Tanzanian and WHO and therefore, a conclusion reached was that the river water quality was affected by mining activities with respect to Ni, Fe and slightly by Zn, which make it unsuitable for human consumption. However, it was also important to note that mining activities were not the only source of pollution in the Bulyanhulu River, as some of the contaminants were detected upstream of the mine. Other sources of the major pollutants detected could be anthropogenic such as land use activities, small industries surrounding the study site and geological nature of the area. The concentrations values of As, Ag, Hg, CN^- and NO_3^- in the river sample points were generally low (below method detection limits).

5.1.2 Effluent Control Ponds (ECP's)

Waste Rock Dump Runoff Pond (WDRP) and Tailings Dam Reclaim Water Pond (TDRP) are Bulyanhulu Gold Mine Effluent Control Ponds characterized as standing water bodies. These ponds had chemical parameter concentrations that exceeded most Tanzanian Water Laws - Mining regulation for effluent discharge (sewage/pond) guidelines EMPC (2006) as expected. The data obtained are indicated in Table 7 and Figs. 13-18. It was decided to discuss their results because if extensive flooding were to occur in this area, the pollution control ponds would influence the Bulyanhulu River. The ECP have effects on local groundwater quality, even though, there was no actual discharge of mine effluents to the river when the study was conducted.

Table 7: Effluent Control Ponds analysis results of heavy metals and non-metallic constituents for ten sampling campaigns (Jan to Mar 2008).

Physico-chemical parameters						
Sampling points	*pH*	*Temp*	*EC*	*$NO3^-$*	*SO_4^{2+}*	*CN^-*
	pH	deg C	µS/cm	mg/l	mg/l	mg/l
WDRP	7.2-7.9 (7.5 ± 0.2)	23.5-27 (26 ± 1.1)	1320-1740 (1562 ± 141)	4.9-8.4 (6.3 ± 1)	625-872 (725 ± 90)	<0.005
TDRP	3.8-6.9 (5.1 ± 1.1)	23.6-28 (26 ± 1.2)	1960-2804 (2376 ± 283)	3.5-7 (4.7 1.2)	971-1662 (1304 ± 261)	<0.005
Heavy metals						
	Ag (mg/l)	*As (mg/l)*	*Fe (mg/l)*	*Hg (mg/l)*	*Ni (mg/l)*	*Zn (mg/l)*
WDRP	0-0.2 (0.1 ± 0.1)	<0.005	5.3-6.9 (6.0 ± 0.5)	<0.005	0.3-1.0 (0.7 ± 0.2)	4-12.5 (8.1 ± 3)
TDRP	0-0.2 (0.1 ± 0.1)	<0.005	2-11.5 (8.5 ± 3.6)	<0.005	0.1-1.3 (0.8 ± 0.3)	9.3-28 (18 ± 6)

Note:

- The range, average and standard deviation is based on 10 values for ten sampling campaigns.
- EC = electrical conductivity, NO_3^- = Nitrate, SO_4^{2+} = Sulphate, CN^- = Cyanide, Ag = Silver, As = Arsenic, Fe =Iron, Hg = Mercury, Ni = Nickel and Zn = Zinc.
- WDRP = Waste Rock Dump Runoff water Pond and TDRP = Tailings Dam Reclaim Water Pond.

- **pH levels of Effluent Control Ponds sampling points**

The pH values on Waste Rock Dump Runoff Pond (WDRP) and Tailings Dam Reclaim Water Pond (TDRP) ranged 3.8 to7.9 throughout the sampling campaign as graphically presented in Fig.13. TDRP is significantly below the 6.5 to 8.5 Tanzanian guideline for effluent discharge due to the nature of water body as described earlier. This could also be caused by runoff of effluents from the process plant where the effluents contains some chemical reagents such as frothers, potassium amyl xanthate (PAX), aerophine 3418A and Methyl Isobutyl Carbinol (MIBC). These chemical reagents are used in the recovery of gold from the sulphide ore, leaving the gangue minerals free in the slurry.

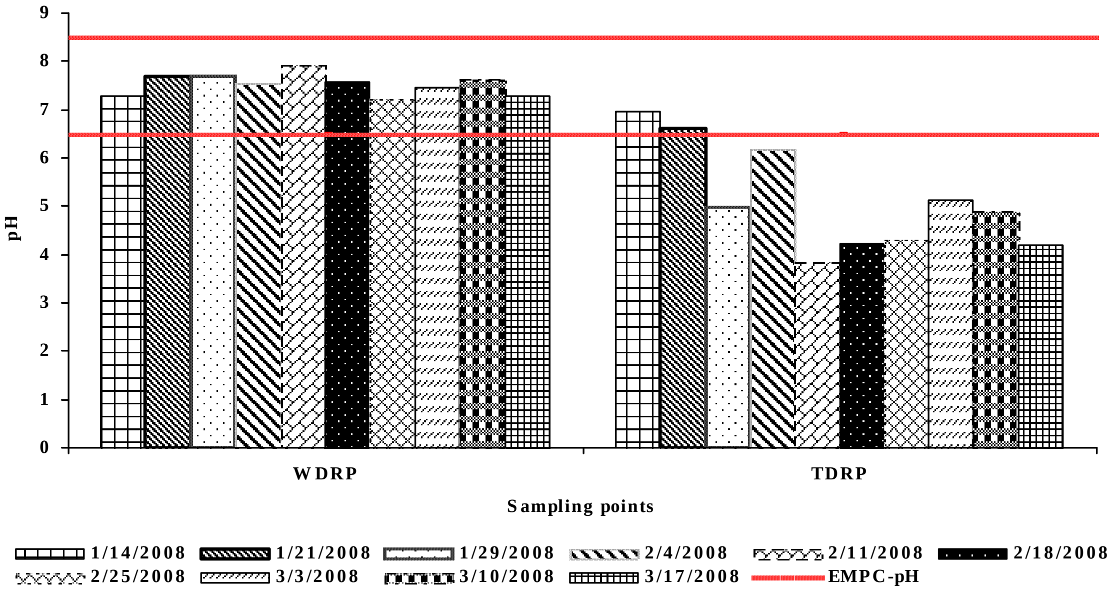


Fig.13. Variation of pH levels among Effluent ponds sampling points.

Note:

- EMPC = receiving water from (sewage/pond) maximum permissible concentration for effluent .
- WDRP = waste dump pond and TDRP = tailings dam pond.

The low pH values could also be due to acid mine drainage (AMD) from the oxidation of sulphides in the tailings materials, which result in the formation of sulphuric acid that tend to lower the pH (Nemerous and Avijit, 1991). This enhances the electrochemical reaction of the sulphide slurry and lowers the pH. As for the case of WDRP, the pH was high because there was a form of treatment (lime addition) in the pond as part of rehabilitation efforts undertaken by mine operators. The neutralization process dilutes the water and raises the pH leaving the water fairly good with elevated pH levels. Acidified water of TDRP may also have had an effect on the groundwater quality of TMB8 monitoring borehole.

The values of pH in TDRP were lower than in WDRP. The low pH values in effluent ponds do not seem to influence the river but possibly influence groundwater quality of PMB2 and TMB8, since the boreholes are 50-70 m from the effluent control ponds.

- **Electrical conductivity values of Effluent Control Pond sampling points**

Conductivity values ranged from 1320 to 2804 µS/cm in Waste Rock Dump Runoff Pond (WDRP) and Tailings Dam Reclaim Water Pond (TDRP) sampling points as indicated in Fig.14 also in Table 7. All EC values in effluent ponds were below the local guideline limit for effluent discharge, the higher conductivity values in WDRP and TDRP are expected due to high content of metallic ions and non metallic ions such as sulphate in water. These are linked to total dissolved solids (TDS) as suggested by Stednick (1991).

The total dissolved solids originate from natural sources, sewage effluent discharges, urban runoff or industrial waste discharges. High levels of TDS mean poor water quality. A study by Malik *et al*. (2003) on the effect of industrial discharges on water quality found the solids from the Tannery industry had depressed effects on plant growth and aquatic species due to total dissolved solids that were released into the stream. In this study the conductivity levels from the mine ponds were high and if there was effluent discharge into the river at the time of sampling it would mean release of contaminated water into the river.

Tanzanian guidelines values of EC were not met in 100% of total results obtained from WDRP and TDRP. The high conductivities possibly influence the groundwater quality of PMB2 and TMB8.

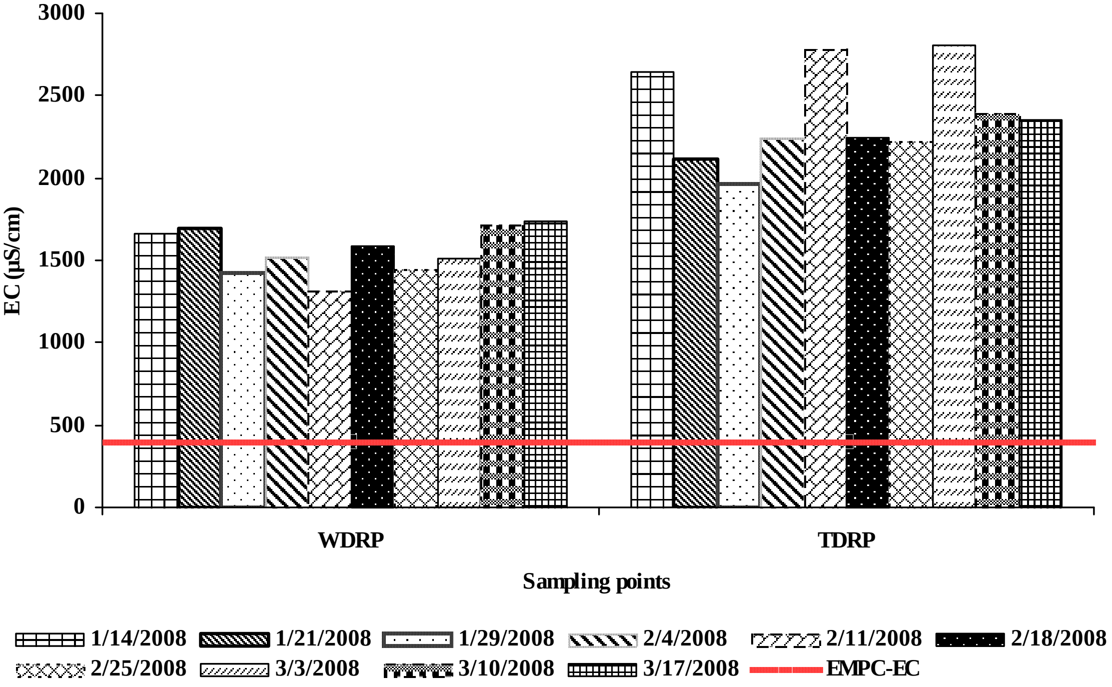


Fig.14. Variation of Conductivity values among Effluent pond sampling points.

Note:

- EMPC = receiving water from (sewage/pond) maximum permissible concentration for effluent .
- WDRP = Waste Dump Pond and TDRP = Tailings Dam Pond.

- **Sulphate concentrations of Effluent Control Pond sampling points**

Sulphate concentrations in all effluent ponds sampling points ranged from 625 to 1662 mg/l as shown in Fig.15. All of the effluent ponds sampling stations were below the 600 mg/l Tanzanian maximum allowable limits of effluent discharge. Sulphate levels in Waste Rock Dump Runoff Pond (WDRP) and Tailings Dam Reclaim Water Pond (TDRP) are likely to have come from the waste rock dump and tailings storage facility runoff or are probably due to the natural geology of the area, which mainly constitute pyrites and chalcopyrite as the by products of sulphide oxidation reaction or acid mine drainage (AMD) introduced to surface system by mining activities (Ripley, 1996). High sulphate levels are normally associated with low pH. In this study the pH for TDRP was ranged from 3.8 to 6.9 and this could explain why there were high levels of sulphate in that pond. Low sulphate levels in WDRP can be explained by the neutralization due to lime addition which is one of the methods used as part of the rehabilitation efforts being undertaken in the mine. Although WDRP and TDRP have showed high values of Sulphate (acidic condition) the sulphate concentrations did not show adverse effects on the local surface water of the Bulyanhulu River during flood events but may have debilitating effect on the groundwater quality. TDRP is lined with a HDPE plastic synthetic liner to prevent seepage of poor water quality in groundwater as shown in Appendix 3 but WDRP is not lined with any material.

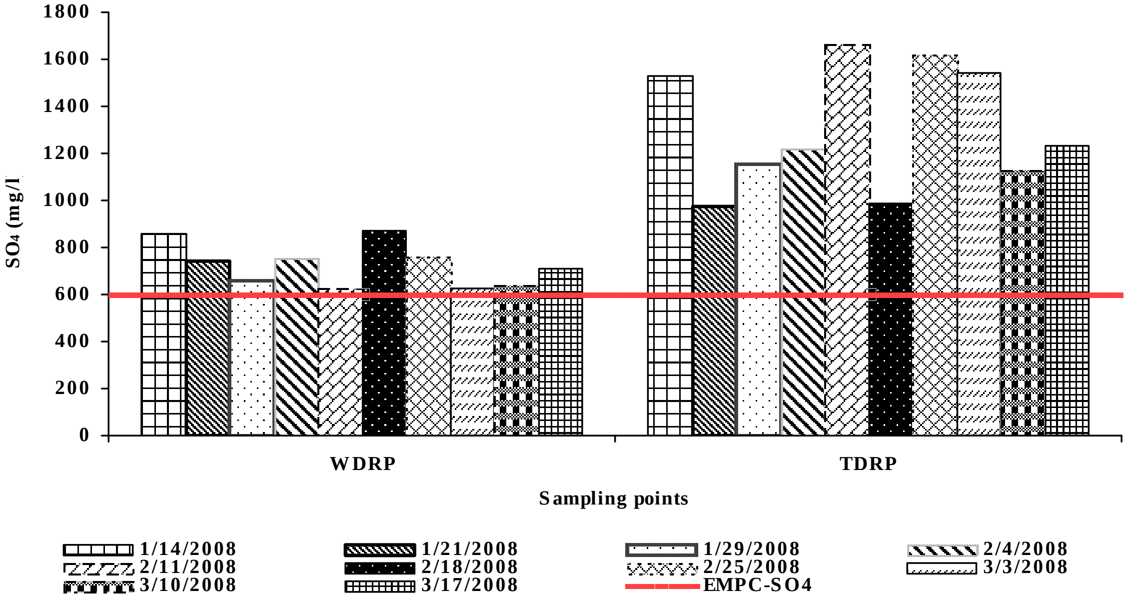


Fig.15. Variation of Sulphate concentrations among effluent pond sampling points.

Note:

- EMPC = receiving water from (sewage/pond) maximum permissible concentration for effluent .
- WDRP = Waste Dump Pond and TDRP = Tailings Dam Pond.

In conclusion, all the effluent ponds, WDRP and TDRP, did not meet the local maximum allowable limit for effluent discharge. When the effluent released into the river might affect the water quality, so far no elevated sulphate levels detected in the river but the effluent ponds may have effect to the groundwater quality of PMB2 and TMB8.

- **Iron concentrations of Effluent Control Pond sampling points**

The concentration of Iron ranged from 2.0 to 11.5 mg/l in all effluent ponds points (Fig.16). An EMPC-Tanzanian value for effluent discharge of 3 mg/l was not met in 100% of results obtained in all stations. The reason could be these standing water bodies Waste Rock Dump Runoff Pond (WDRP) and Tailings Dam Reclaim Water Pond (TDRP) are in contact with the tailings storage facility and the waste rock dump in the mine, which mainly constitute heavy metals from sulphide originally bound within the ore bodies as pyrites (FeS_2) and Chalcopyrite ($CuFeS_2$) as noted by Kahatano *et al*. (1995), Ripley (1996) and Shuttle (2005). High concentrations of Iron measured in the effluent ponds would indicate effluents of very high iron concentration. This could influence the aquatic behavior when discharged into the river. In fact on visual observation of these effluent ponds the water was in orange color, which is indicative of high iron concentration.

DWAF (1996) suggests that the chemical behavior of iron in the aquatic environment is determined by oxidation-reduction reactions, pH and the presence of co-existing inorganic and organic complexing agents. Thus some of these factors may have been present at sampling points during the monitoring period. The determination of these factors in order to determine the behavior of iron in the aquatic environment was not studied.

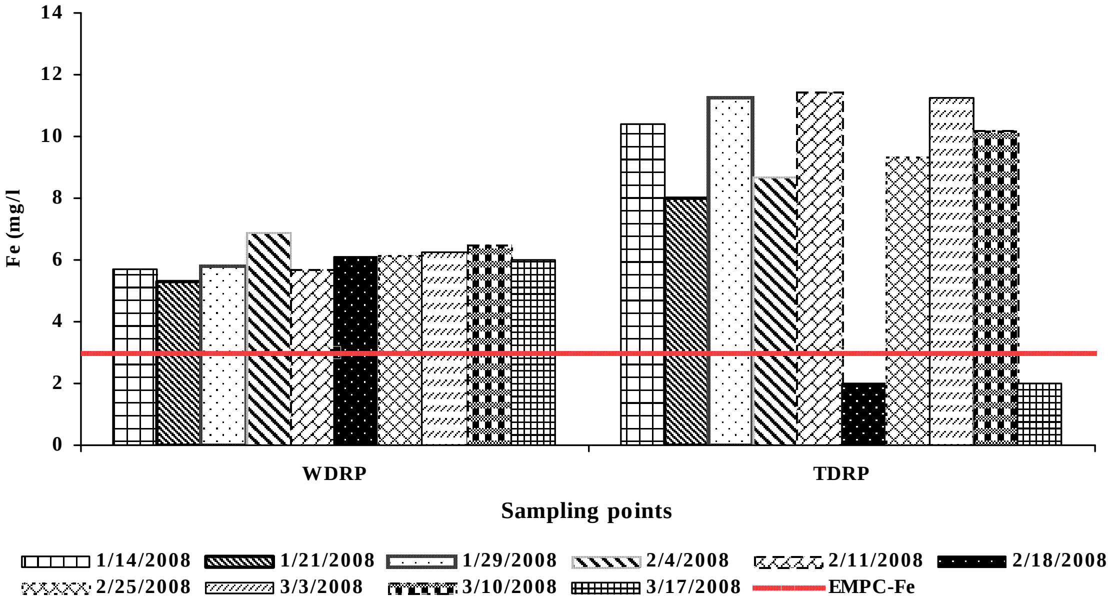


Fig.16. Variation of Iron concentrations among Effluent pond sampling points.

Note:

- EMPC = receiving water from (sewage/pond) maximum permissible concentration for effluent.
- WDRP = Waste Dump Pond and TDRP = Tailings Dam Pond.

In summary, the Iron concentrations were found to be high in both effluent ponds. The elevated values measured were attributed to mine waste dump and tailings materials from mining activities, which had potential effects on surface and groundwater quality.

- **Nickel concentrations of Effluent Control Pond sampling points**

Nickel concentrations in all effluent ponds ranged from 0.1 to 1.3 mg/l as shown on Fig.17. The maximum nickel permissible level of effluent water by Tanzanian guideline is 0.5 mg/l. High nickel values in water samples from Waste Rock Dump Runoff Pond (WDRP) and Tailings Dam Reclaim Water Pond (TDRP) was probably due to nickel nitrate from the underground mine, which dissociates in acidic water and leaves free nickel (Ni) ions, thereby increasing the nickel concentrations in the ponds (Ashley *et al.*, 2003). The high levels of nickel were also likely to have come from the waste dump stockpiles, which contained high nickel contents. The water runoff from waste dump stockpiles accelerates the dissociation of nickel and hence causes elevated levels of nickel in the receiving environment. A study by Lupakwa *et al*. (2006) on the influence of the Trojan Nickel Mine in Bindura Zimbabwe on surface water quality found elevated levels of Ni in Pote River as a result of mine effluents. Since Bulyanhulu River in the study area receives effluents from BGM ponds and the effluents had shown high levels of Ni it is therefore important for the mine operators to decrease the Ni loads. This could be achieved by treating the water with lime as it enters the pond, thus raising the pH and precipitating the Nickel in the pond.

WDRP and TDRP had all shown higher levels of Ni as compared to Tanzanian guidelines for effluent water quality, indicating the water is unsuitable for domestic and agricultural purposes if discharged into the river and would cause effect in the associated boreholes.

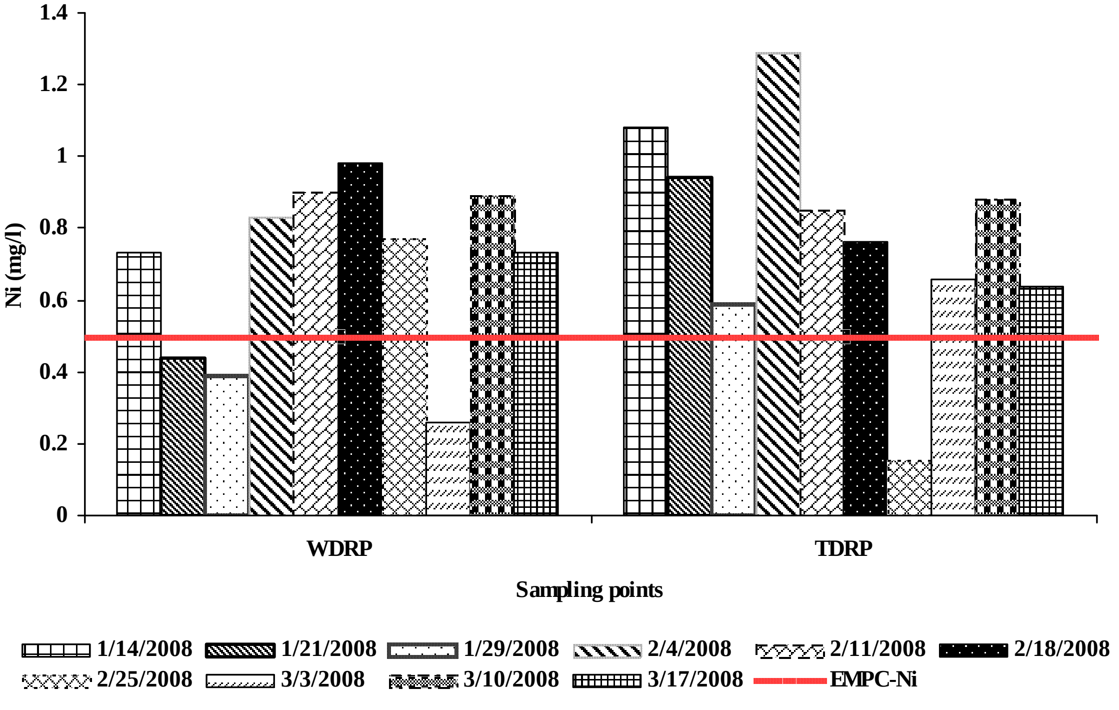


Fig.17. Variation of Nickel concentrations among Effluent pond sampling points.

Note:

- EMPC = receiving water from (sewage/pond) maximum permissible concentration for effluent .
- WDRP = Waste Dump Pond and TDRP = Tailings Dam Pond.

- **Zinc concentrations of Effluent Control Pond sampling points**

Zinc concentrations ranged from 4.0 to 27.8 mg/l in all effluent pond sampling points as indicated in Fig.18. Values of Zn were all above the Tanzanian guidelines acceptable level of 1mg/l for effluent discharge. The increase of Zinc contamination in Waste Rock Dump Runoff Pond (WDRP) and Tailings Dam Reclaim Water Pond (TDRP) may be related to mine waste dumps that could be from the decay and decomposition of carbon-Zinc discarded batteries which dissociates in acidic form, leaving free Zn in water. Zinc-carbon batteries are composed of a manganese-dioxide-and-carbon cathode, a Zinc anode, and Zinc chloride as the electrolyte which is illustrated by the Equation 5. Zinc contamination could also be due to oxidation of sphalerite (ZnS) from mineralized veins and oxidation of Zinc fillings used to precipitate gold in the cyanidation process (Kahatano *et al*., 1995).

$$Zn + 2MnO_2 + 2NH_4Cl \rightarrow Zn(NH_3)2Cl_2 + 2Mn(OH)_2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(5)$$

The effects of discarded batteries on the environment were similar to that observed by Lenntech (2004), who found that discarded batteries pollute soils and water by increasing heavy metal contents. During rainy season, mine wastes are leached and add heavy metal ions such as Zn, Cu and Ni to the water. Similar phenomena were observed by Linda (2002) and Orem (2005) who observed that weathering, leaching and soil erosion in mining areas also contribute to water and soil pollution due to release of heavy metal ions.

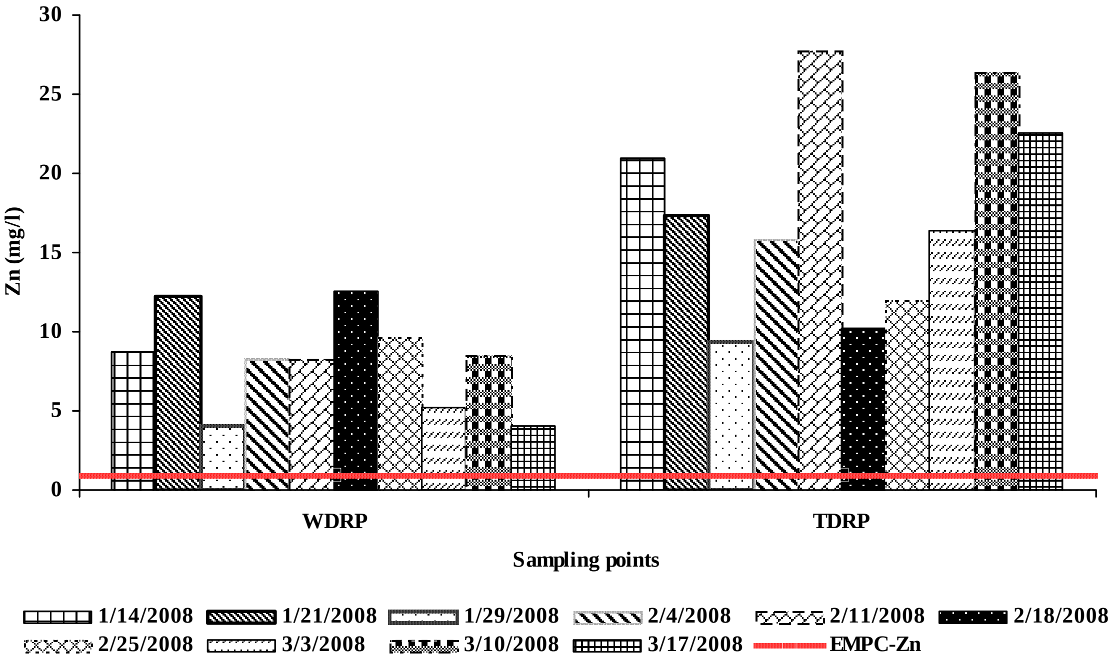


Fig.18. Variation of Zinc concentrations among Effluent pond sampling points.

Note:

- EMPC = receiving water from (sewage/pond) maximum permissible concentration for effluent .
- WDRP = Waste Dump Pond and TDRP = Tailings Dam Pond.

Effluents from mine ponds into streams and rivers contain high concentrations of heavy metals, which cause danger to species especially those which are dependent on streams and rivers. Ntengwe and Maseka (2006) found that almost all fish species in the Chambishi and Mwabishi streams exhibited stunted growth due to mine effluents containing high levels of Zn and Ni.

Concluding remarks for Effluent ponds water quality

It was observed that all effluent ponds had exceptionally high concentrations of all elements studied with exception to As, Ag, Hg, CN and NO_3^-, which were found to be below the method detection limit of <0.005 mg/l. High concentrations of these parameters could affect surface and groundwater system if management strategies are not established.

5.1.3 Groundwater

The results presented in this section are based on the individual statistical results of non - metallic constituents and heavy metals studied at each sampling point as shown in Table 8 and Table 9, which summarise the ranges, averages, and standard deviations for nine sampling campaigns. Figs.19-24 presents the principal heavy metals and non metallic variation among sampling points compared to RMPC (2006) and WHO (1998) guidelines for drinking water quality. Monitoring boreholes were compared to drinking water quality guidelines because some of the boreholes drilled by the mine operators were used for domestic uses.

According to WEGS (2002), the majority of groundwater flow at Bulyanhulu Gold Mine (BGM) is associated with localized shallow sand or gravel layers (<5 m below ground level) and fissures within the lower hard and leached clay horizons. The fissured zones create localized pathways of higher permeability. The groundwater generally flows in the direction of the Bulyanhulu River.

The water quality parameters evaluated for groundwater were the following; pH, EC, CN, SO_4, NO_3-N, Fe, Hg, As, Ag, Ni and Zn. A description of these parameters was given in section 5.1.1. Only results exceeding Tanzanian and WHO guidelines were discussed in this section. The groundwater sampling points were labeled as Plant Site Monitoring Borehole 2 (PMB2), Tailings Dam Monitoring Borehole 8 (TMB8), shallow well one (SW1) and shallow well two (SW2). SW1 and SW2 are community shallow wells located 3.5 km and 1km respectively away from the BGM project.

This section also describes the relationship between the groundwater quality of boreholes and Effluent Control Ponds within the mine site. It also tries to find out if Effluent Control Ponds WDRP and TDRP water quality impacts on the groundwater quality of PMB2 and TMB8 since these boreholes are located 50-70 m from the effluent ponds.

Table 8: Groundwater water analysis results (non-metallic constituents) for the nine sampling periods (Jan 21st to Mar 17th).

Sampling points	*pH*	*EC*	*NO_3^-*	*SO_4^{2+}*	*CN^-*
	pH	*uS/cm*	*mg/l*	*mg/l*	*mg/l*
SW1	4.4-5.5 (5 ± 0.3)	280-350 (310 ± 21)	6-9 (7.3 ± 0.8)	0.5-181 (21 ± 60)	<0.005
SW2	5-5.8 (5.3 ± 0.3)	80-120 (95.6 ± 12)	0.5-1 (0.9 ± 0.2)	0.1-0.5 (0.5 ± 0.2)	<0.005
TMB 8	5.6-6.5 (6.2 ± 0.4)	520-800 (608 ± 96)	1.4-2.7 (2 ± 0.4)	198-636 (327 ± 149)	<0.005
TMB8 (Control) Jan-Mar_2001	5.3-7.1 (6.2 ± 0.9)	41-63 (52 ± 11)	1.5-8 (4.2 ± 3)	0.5-20 (7.1 ± 11)	<0.005
PMB2	5.2-5.9 (6.1 ± 0.3)	520-1730 (1438 ± 357)	6.2-9 (7.3 ± 1)	609-757 (666 ± 54)	<0.005
PMB2 (Control) Jan-Mar_2001	5.2-5.8 (5.4 ± 0.3)	190-208 (197 ± 9.5)	0.4-3 (1.5 ± 1.3)	0.5-6.2 (2.4 ± 3.3)	<0.005

Note:

- The range, average and standard deviation is based on 9 values for nine sampling campaigns.
- EC = electrical conductivity, NO_3^- = Nitrate, SO_4^{2+} = Sulphate, CN^- = Cyanide.

Table 9: Groundwater analysis results (heavy metals) for the nine sampling periods

Sampling points	*Ag*	*As*	*Fe*	*Hg*	*Ni*	*Zn*
	mg/l	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*
SW1	<0.005	<0.005	0.1-0.1 (0.1 ± 0.0)	<0.005	0.1-0.3 (0.2 ± .1)	2.2-4.1 (3 ± 0.6)
SW2	<0.005	<0.005	0.1-0.3 (0.3 ± 0.1)	<0.005	0	1.1-2.5 (2 ± 0.6)
TMB 8	0-0.1	<0.005	0.1-1.0 (0.3 ± 0.4)	<0.005	0	2.0-4.6 (3 ± 1.0)
TMB8 (Control)	0.2-0.5	<0.005	0.5-0.6 (0.5 ± 0.1)	<0.005	0-0.1	0.1-0.5 (0.4 ± 0.2)
PMB2	<0.005	<0.005	0.0-0.4 (0.1 ± 0.2)	<0.005	0-0.1	2.5-10.7 (5 ± 2.5)
PMB2 (Control)	<0.005	<0.005	0.1-1.2 (0.5 ± 0.6)	<0.005	0-0.1	<0.005

Note:

- The range, average and standard deviation is based on 10 values for ten sampling campaigns.
- Ag = Silver, As = Arsenic, Fe =Iron, Hg =Mercury, Ni = Nickel and Zn = Zinc.
- SW1 and SW2 = community shallow wells, TMB8 = Tailings Dam Monitoring Borehole and PMB2 = Plant Site Monitoring Borehole.

- **pH levels of groundwater sampling points**

The pH ranged from 5.2 to 6.5 in boreholes and from 4.4 to 5.8 in shallow wells, as indicated in Fig.19 also in Table 8. Values recorded for boreholes were relatively close to those of the controls measured in Jan-Mar 2001 before the initiation of the Bulyanhulu Gold Mine activities although they peaked at Tailings monitoring borehole -TMB8 (control). The accepted range of Tanzanian water quality guidelines for drinking water quality is 6.5-8.5. All sampling points for both boreholes and shallow wells had pH values lower than the required guidelines.

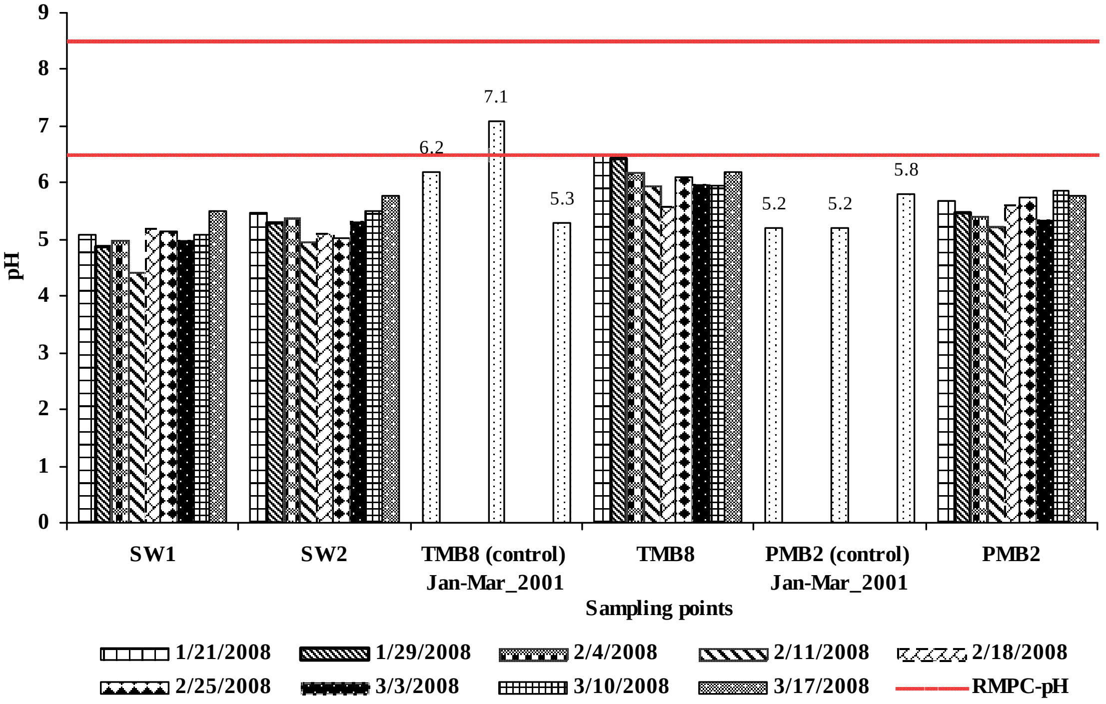


Fig.19. Variation of pH levels among groundwater sampling points.

Note:

- RMPC = receiving water (potable/groundwater) maximum permissible concentration guideline .
- SW1 and SW2 (shallow wells), PMB2 = Plant Site Borehole and TMB8 = Tailings Dam borehole.

Low values of pH in boreholes can be attributed to seepage of acidic effluents from the mine waste dumps and Effluent Control Ponds. TMB8 is located close to tailings storage facility and TDRP that collects all the surface water runoff around the tailings area and PMB2 close to waste rock dump it is thus probable that there were higher concentrations of pyritic materials (AMD) in sulphide ores, which when oxidized produce ferrous sulphate and sulphuric acid. This resulted in a pH range of 2.0-4.5 in the receiving water (Warnick, 1989). Low pH values recorded at residential shallow wells could have been due to the natural geology of the area, which is acidic in nature with larger quantities of dissolved minerals. As water moves through the soil and rocks, it dissolves small amount of minerals and holds them in solution. According to Mason (1993) the pH of pure water is 7 at 25°C, but when exposed to CO_2 in the atmosphere this equilibrium results in a pH of approximate 5.2 and therefore, there is an association between pH, atmospheric gases and temperature. Therefore these factors could have contributed to the low pH observed in shallow wells.

It can be concluded that the groundwater samples analyzed with respect to pH were highly affected by the infiltration/seepage from Effluent Control Ponds and mine waste dumps, since the pH values varied considerably between ponds and boreholes.

- **Conductivity values of groundwater sampling points**

Conductivity values for both borehole sampling points were found to be in the range of 52 to1730 µS/cm and 80 to 350 µS/cm in shallow wells points as presented in Fig.20 and Table 8. The Tanzanian drinking water guideline of 2006 for conductivity is 400µS/cm. Low levels of EC below Tanzanian guidelines were recorded in both shallow wells. Both boreholes seemed to exceed the acceptable level of water quality. Values of EC in Plant site Monitoring Borehole (PMB2) had increased by 88$^{\%}$ compared to control values recorded in 2001. An increase of 92$^{\%}$ compared to background levels was recorded at Tailings Dam Monitoring Borehole (TMB8).

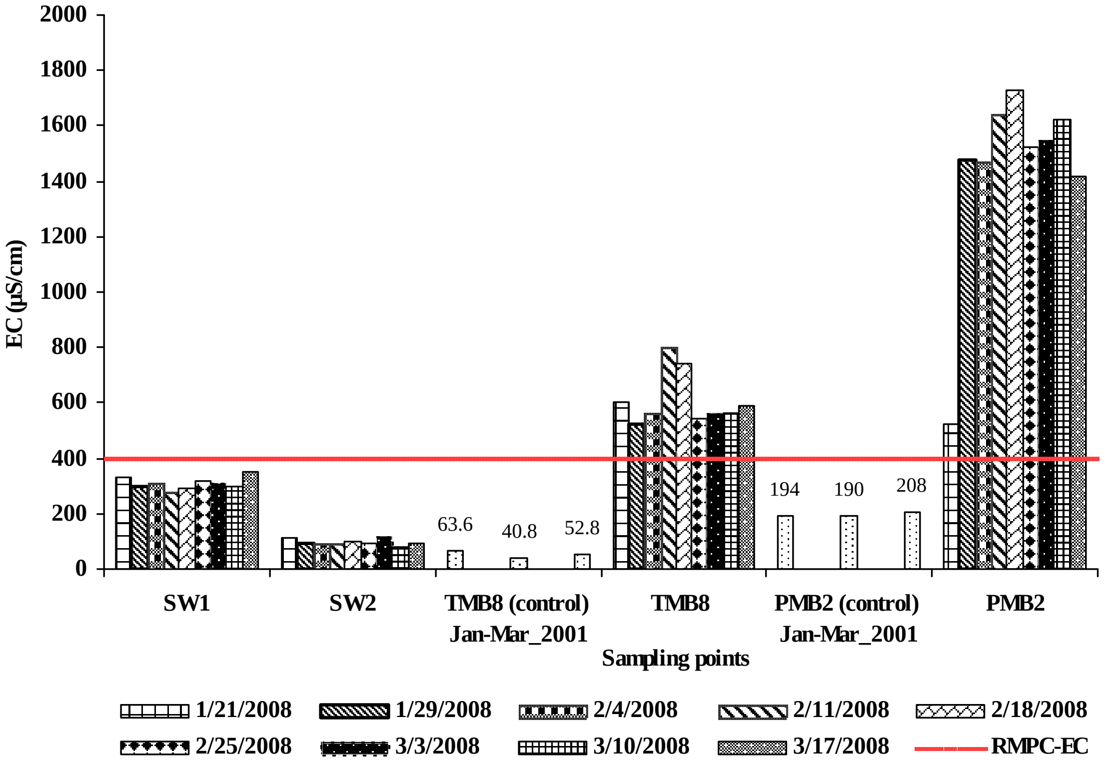


Fig.20. Variation of Conductivity values among groundwater sampling points.

Note:

- RMPC = receiving water (potable/groundwater) maximum permissible concentration guideline.
- SW1 and SW2 (shallow wells), PMB2 = Plant Site Borehole and TMB8 = Tailings Dam Borehole.

Tailings Dam Monitoring Borehole (TMB8) seemed to have slightly lower values compared to Plant site Monitoring Borehole (PMB2). A report by Golders (2004) on preliminary evaluation of seepage quality and volume on the tailings side of the mine found that seepage was likely to be generated from the tailings reclaim pond (TDRP) at the rate of 215m^3/d and from tailings storage facility (average 40m^3/d); a recommendation made was to line the pond so as to avoid the infiltration of poor water quality in groundwater system. The mine has recently implemented the recommendation and hence there were lower values of conductivity at TMB8. The pond adjacent to this borehole, which receives effluents from tailings storage facility, has been lined with a synthetic plastic liner (HDPE) and paste tailings with low net percolation rates so as to prevent seepage of poor water quality from the tailings pond to groundwater this is shown in Appendix 3. High levels of EC in PMB2 could be due to seepage from the waste rock dump and Waste Rock Dump Pond (WDRP) as this pond is not lined with any materials.

It was thus concluded that with respect to conductivity, the groundwater quality in boreholes has been affected by mining activities, and that the excessive conductivity is probably attributed to high sulphate and heavy metal concentrations due to seepage from effluent ponds.

- **Sulphate concentrations of groundwater sampling points**

The concentrations of sulphate for boreholes ranged from 198 to757 mg/l and 0.1 to 181 mg/l (in shallow wells) as indicated in Fig.21.

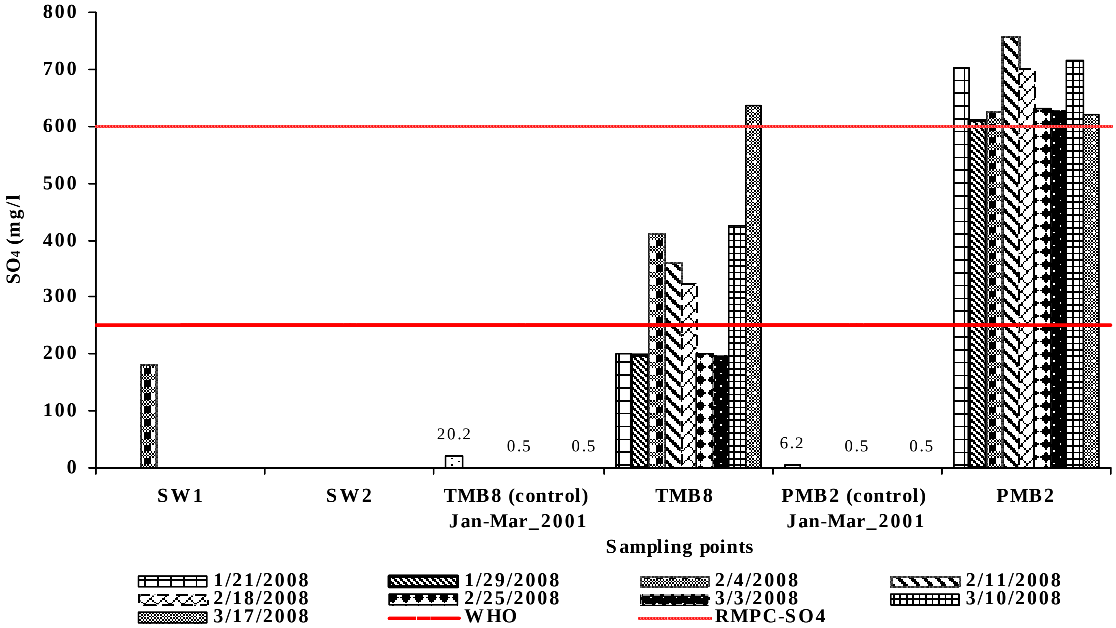


Fig.21. Variation of Sulphate concentrations among groundwater sampling points.

Note:

- RMPC = receiving water (potable/groundwater) maximum permissible concentration guideline and WHO = world health organization guideline
- SW1 and SW2 (shallow wells), PMB2 = Plant Site Borehole and TMB8 = Tailings Dam Borehole.

It can be seen that monitoring boreholes values deviate greatly from the WHO (1998) of 250 mg/l and 600 mg/l RMPC (2006) drinking water quality guidelines. The control values measured were very low for sulphate. Higher sulphate content in boreholes reflects the oxidation of pyrites in the generation of acid mine drainage in the Effluent Control Ponds (WDRP and TDRP), waste rock dump and tailing storage facility that have clearly shown that the water chemistry is dominated by acid mine drainage.

A similar study on evaporation ponds at IDM conducted by Ravengai *et al*. (2004) showed that the effluent ponds were generating large quantities of acid, iron and sulphate that were seeping into groundwater, which is relatively the same with this study. Both shallow wells had sulphate levels lower than the WHO and Tanzanian guidelines. Slightly high level of sulphate was measured once in SW1. This was probably due to contamination during sampling.

Therefore, it was concluded that the higher sulphate concentrations in groundwater quality of boreholes are linked to mining activities.

- **Nickel concentrations of groundwater sampling points**

Nickel concentrations ranged from 0 to 0.1 mg/l in both boreholes and 0 to 0.3 mg/l in shallow wells as presented graphically in Fig. 22.

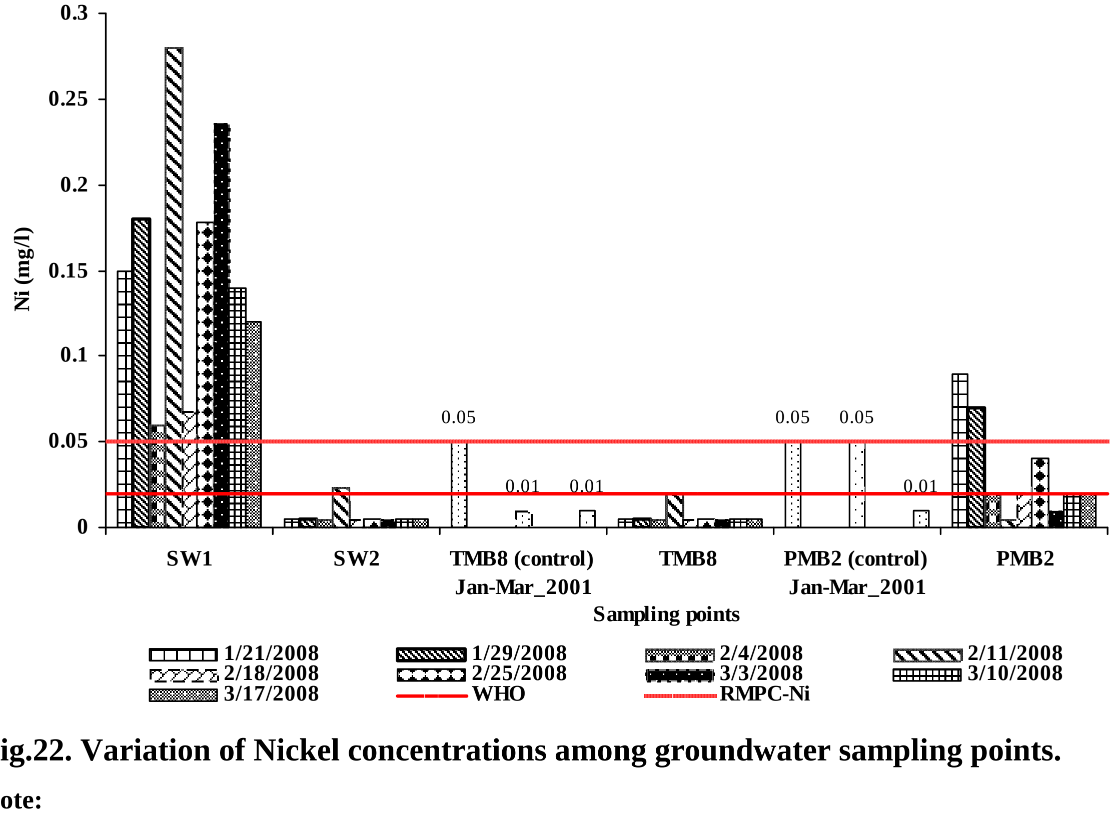


Fig.22. Variation of Nickel concentrations among groundwater sampling points.

Note:

- RMPC = receiving water (potable/groundwater) maximum permissible concentration guideline and WHO = world health organization guideline
- SW1 and SW2 (shallow wells), PMB2 = Plant Site Borehole and TMB8 = Tailings Dam Borehole.

The Tanzanian guidelines for drinking water are 0.05 mg/l and 0.02 mg/l for WHO. Tailings Dam Monitoring Borehole (TMB8) met the required guidelines limits. Values of Nickel at Plant site Monitoring Borehole (PMB2) exceeded both guidelines by 66% (WHO) and 33% (Tanzanian). High levels of Nickel were directly associated with seepage from Effluent Control Pond (WDRP) as described in section 5.1.2.

High concentrations of Ni exceeding guidelines were measured at SW1 throughout the sampling period at this point the contamination could be due to small industries in the surrounding village, artisinal mining activities that are very close to this point and probably due to geological nature of the area.

In conclusion, the analysis of results revealed that SW1 had higher concentration values of Nickel than other sampling points and the groundwater quality of PMB2 was affected by mining activities. Therefore, mining communities that use water from SW1 are therefore prone to Ni health hazards which are related to survival, growth, reproduction, development behavior and metabolism (ATSDR, 2005).

- **Zinc concentrations of groundwater sampling points**

Zinc concentrations ranged from 2.0 to 10.7 mg/l in all borehole samples and 1.1 to 2.5 mg/l in shallow wells as indicated in Fig.23. The Tanzanian and WHO guidelines for drinking water quality are 0.2 mg/l and 3 mg/l respectively.

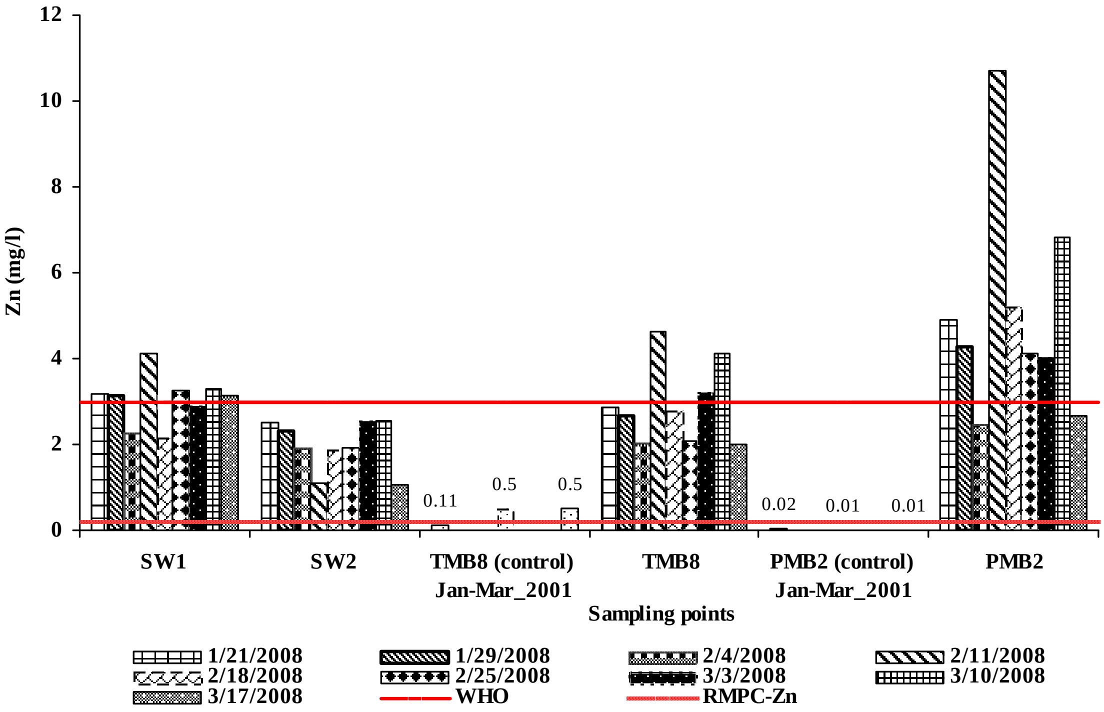


Fig.23. Variation of Zinc concentrations among groundwater sampling points.

Note:

- RMPC = receiving water (potable/groundwater) maximum permissible concentration guideline and WHO = world health organization guideline
- SW1 and SW2 (shallow wells), PMB2 = Plant Site Borehole and TMB8 = Tailings Dam Borehole.

Both borehole sampling points exceeded the guidelines and control value levels and thus there are high concentrations of Zinc in the groundwater system. Zinc values for Tailings Dam Monitoring Borehole (TMB8) had increased by 76$^{\%}$ compared to the background levels and 98$^{\%}$ increase at Plant site Monitoring Borehole (PMB2). Values of Zinc in Effluent Control Ponds (WDRP and TDRP) were very high and it is possible that with infiltration and seepage the underground aquifers of PMB2 and TMB8 have been contaminated by these standing water bodies and hence may have affected the groundwater quality.

High levels of Zinc were also found in both shallow wells, they may be associated with anthropogenic sources, galvanized scraps, cast metal (Zn-Pb), brass (Zn-Cu), dry cells, vulcanized rubber and Zinc oxides (white pigment) as noted by (Kahatano *et al*., 1995).

Concluding remarks for groundwater quality results

From the given discussion of groundwater results, it was concluded that, the concentrations values of As, Ag, Hg, CN^- and NO_3^- in the groundwater samples were low (within the acceptable values and were close to background levels in water). The ground water quality was affected by mining activities with respect to pH, EC, SO_4^{2+}, Ni and Zn however; EC and SO_4^{2+} appeared to affect more the monitoring boreholes.

5.2 Quantification of indicative potential pollutant loads in Bulyanhulu River

Given the need for good water quality in the Bulyanhulu River, there was a need to establish the potential pollutant loads reaching the river. Potential loads in Effluent Control Pond WDRP and TDRP were also calculated. The quantification method was based on a mass balance equation according to Cho *et al*. (1991) and Riza (2000). Table 10 presents the indicative potential pollutant loads in kg/day for each river point and effluent ponds, while Table 11 shows the indicative potential concentration mix in (mg/l) of each pollutant in both waste dump runoff pond (WDRP) and river points upstream the mine at (W2, W3 and W4).

Potential pollutant loads in Bulyanhulu River water samples were based on 0.71 m^3/s average flow data for the wet season (Jan-Mar 2003). Data for the period March 2002 through February 2003 from the Bulyanhulu River gauging station is given in Appendix 4. Flows for 2008 could not be obtained because the gauging station was vandalized in 2004. The flow for Effluent Control Ponds were based on a volume of 18354 m^3 of effluents discharged into the river in 2007 for a period of 3 days from waste dump effluent pond (WDRP).

There was no actual effluent discharge into the river at the time of the study, so what was determined were the assumed potential loads and indicative concentration mix of pollutants that would have been discharged from mine ponds in that period of time.

Table 10: Potential pollution loads among river sampling points and effluent ponds for the period of 14th Jan to 17th Mar 2008.

Values in (kg/day)						
	River points				*Effluent ponds*	
Pollutants	*W1*	*W2*	*W3*	*W4*	*WDRP*	*TDRP*
Fe	205.23	207.15	298.58	44.76	36.93	52.14
Ni	28.13	35.80	28.77	8.31	4.23	4.78
Zn	80.56	171.35	100.38	127.87	49.93	109.87
SO_4	3118.80	4437.16	5114.88	0.00	4444.37	8002.94
P_{TL}	3432.72	4851.46	5542.61	180.94	4535.47	8169.73

Note:

- P_{TL}= Pollution total load
- Fe = Iron, Ni = Nickel, Zn = Zinc and SO_4^{2+}= Sulphate.
- W1=1st point upstream the mine, W2 = 2nd point close to mine site about 600 m, W3 = 3rd point downstream and W4= further downstream of Bully River at Sound Smith of Lake Victoria.

Table 11: Indicative potential pollutant concentration in river points (a mix of river and WDRP pollutants) for the period of 14th Jan to 17th Mar 2008.

Pollutants	*River points (values in mg/l)*			
	W1(original mean concentrations)	*W2*	*W3*	*W4*
Fe	3.21	3.29	8.59	0.70
Ni	0.44	0.56	0.45	0.14
Zn	1.26	2.78	1.70	2.12
SO_4	48.78	81.96	92.36	3.90
T_C	53.69	88.60	103.99	6.86

Note:

- T_{C} = Total concentrations
- Fe = Iron, Ni = Nickel, Zn = Zinc and SO_4^{2+}= Sulphate.
- W1=1st point upstream the mine, W2 = 2nd point close to mine site about 600 m, W3 = 3rd point downstream and W4= further downstream of Bully River at Sound Smith of Lake Victoria.

The concentrations of mean sulphates in river points showed increasing values substantially downstream from the mine at W1 (48.8mg/l) to W3 (80.0 mg/l) representing the potential daily loads of 3119 and 5115 kgs respectively. No sulphate was found at W4 point as shown in Table 10.

A trend of increasing sulphate loads possibly related to inputs from mining activities, the geology of the area and anthropogenic sources. There was an increase in the potential sulphate concentration mix calculated from the mass balance equation downstream of the river from W2, which is close to mine effluent discharge point (600 m downstream of the mine to W3). The levels decreased at W4 were sulphates were diluted.

The mean sulphate loading levels were also found to be high in Waste Dump Runoff Pond (WDRP) and Tailings Dam Reclaim Water Pond (TDRP) ranged from 724.5 to 1304 mg/l respectively represented 4444.4 to 8002.9 kg loads per day this indicated that effluents of such high sulphate concentration could have been disposed into the river when the study was conducted.

The highest mean concentrations for iron (4.7 mg/l) and (3.2 mg/l) in river points with a potential daily load of 299 and 207 kgs were recorded at W3 and W2. The lowest mean concentrations were recorded at points W1 (3.2 mg/l) and W4 (0.7 mg/l) represented 205 and 45 kgs/day.

The indicative potential iron concentration mix was found to be high at W3 and decreased downstream the mine at W4 point where natural purification of the river was high. Elevated iron levels might be related to the presence of pyrites (FeS_2) and Chalcopyrite ($CuFeS_2$) in the ore body. The iron concentrations and loads in WDRP and TDRP ponds were 6.0 mg/l, 36.9 kgs/day and 8.5 mg/l, 52.1 kgs/day respectively.

The indicative potential concentration (mix) of Nickel decreased downstream with distance from near the point of discharge at W2. There was a sharp decrease of Nickel concentrations at W4 as the water enters the Lake Victoria due to dilution and settling effects. The potential loads were found to be high at three river points from W1 going downstream to W3 (Table 10).

Highest mean concentrations of Nickel were recorded at W2 (0.6 mg/l), W3 (0.5 mg/l) and W1 (0.4 mg/l) with the respective potential loads of 36, 29 and 28 kgs/day. The lowest mean concentrations were measured at point W4 (0.1 mg/l), which represented load of 8 kgs/day. Highest concentrations were linked to land use activities and geological nature of the area where by surface water is contaminated via base flow. Levels of nickel in WDRP and TDRP ponds were 0.7 and 0.8 mg/l, which represented daily loads of 4.2 and 4.8 kgs.

The readings for Zinc showed an increased concentrations and potential loads downstream of the mine from W1 (1.3 mg/l, 81 kgs/day), and W2 (2.7 mg/l, 171 kgs/day). Readings for W3 and W4 were (1.6 mg/l, 100 kgs/day) and (2.0 mg/l, 128 kgs/day) respectively.

The Waste Dump Runoff Pond (WDRP) and Tailings Dam Reclaim Water Pond (TDRP) Zinc concentrations were 8.1 and 17.9 mg/l, which represented potential loads of 49.9 and 8002.9 kgs/day. The values of concentration mix for Zinc increased downstream of the mine and peaked at W4. This indicates that effluents with high concentration of Zinc could have potentially been discharged into the river.

Concluding remarks for the pollutant loads into the Bulyanhulu River

In summary, the analysis of results revealed that the potential indicative total concentration (mix) for all pollutants in the river showed an increasing trend of pollutants from station W2 of the river close to mine discharge point to W3 and a sharp decrease far downstream the river at W4 was observed. High potential pollutant loads were measured at W1-W3 points and low pollutants were found far downstream the river at W4 with exception of Zinc which appeared to be high. There were low potential pollutant loads in Waste Dump Runoff Pond (WDRP) and Tailings Dam Reclaim Water Pond (TDRP) compared to loads in the river. This indicated that there were other pollutant sources contributed to poor water quality in the river rather than the mine itself.

5.3 Spatial variation of pollutants in water samples among sampling classes

In order to make conclusions on the results obtained, results were interpreted in terms of spatial distribution for each principal parameter, both surface and groundwater together. Thus, this section shows the variation of pollutants in four categories namely; Bulyanhulu River (upstream and downstream), boreholes, wells and mine Effluent Control Ponds.

The mean concentrations of the pollutants in each category were used to show how the pollutants were spread in different water sampling classes. Figs.24-29, shows interpretations of the spatial distribution of principal heavy metals (Fe, Ni and Zn) and non metallic constituents (SO_4^{2+}, pH and EC) in water samples by using digital elevation models (DEM).

The spatial distribution of parameter concentrations (z) (measured in mg/l with exception for pH and electrical conductivity, which are measured in pH unit and μS/cm respectively). The concentrations of the parameters measured for the entire sampling campaigns were plotted in relations to geographic positions using GPS coordinates from different study sites. X-axis was Eastings and Y-axis was Northings. They were both in Universal Transverse Mercator (UTM).

5.3.1 Spatial distribution of pH level among sampling sites

The pH level in the river class was above 7.1 which reflected background levels followed by mine ponds (Fig.24). The value decreased to 5.17 in community shallow wells. Low pH in mine ponds increases the solubility and mobility of heavy metal ions resulting in water with high total dissolved solids and high conductivity.

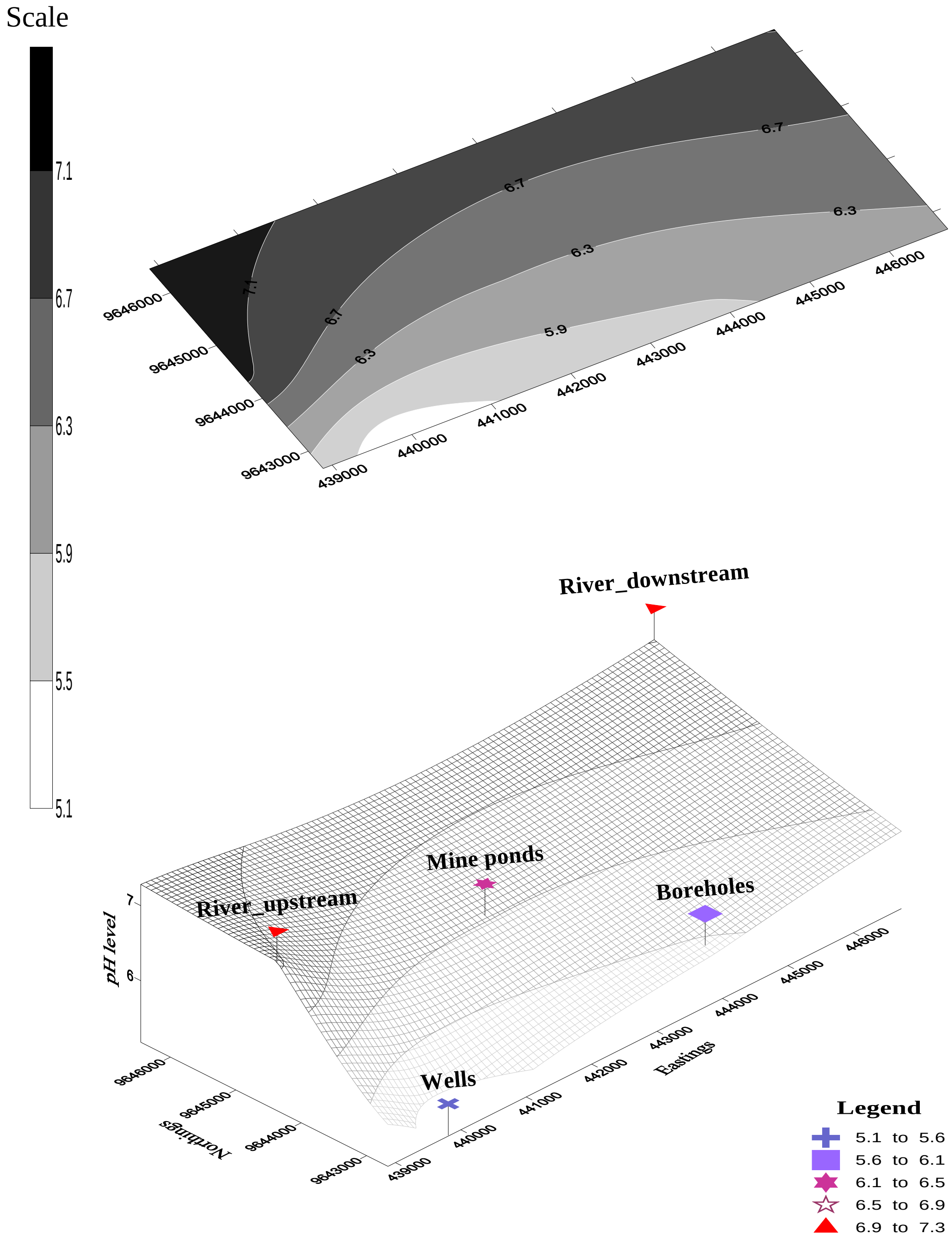


Fig.24. Contour map and DEM showing the mean levels of pH at different sampling classes for the period of 14th Jan to 17th March 2008.

5.3.2 Spatial distribution of electrical conductivity among sites

Water samples from mine effluent ponds show the highest electrical conductivity values. The value of EC in mine ponds was 1969 µS/cm followed by boreholes (1023 µS/cm) as indicated in Fig.25. The value decreased to 176 µS/cm downstream the river, which reflected background values.

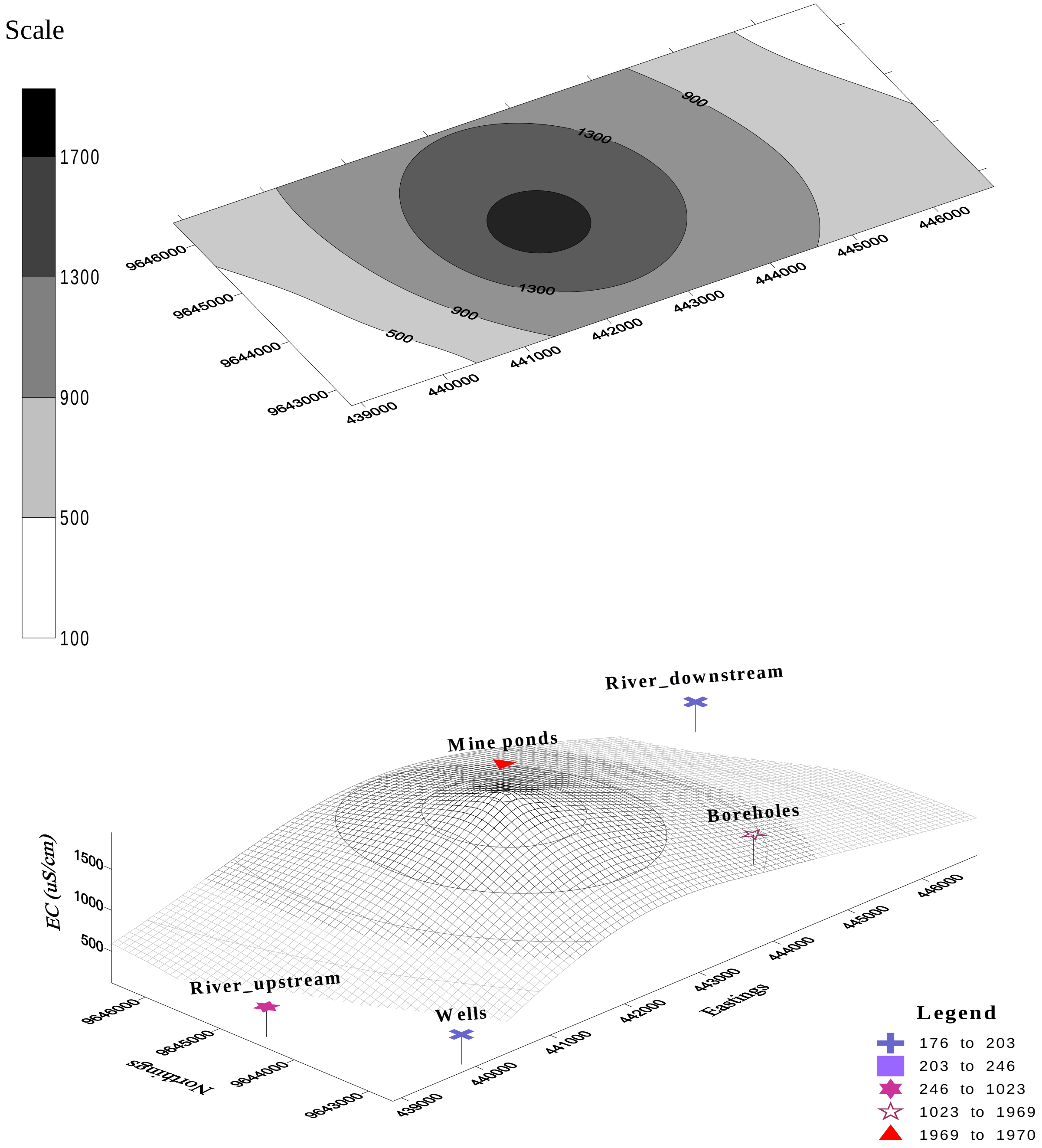


Fig.25. Contour map and DEM showing the mean values of EC at different sampling classes for the period of 14th Jan to 17th March 2008.

5.3.3 Spatial distribution of sulphate levels among sites

Sulphate shows elevated concentrations (maximum value of 1014.55 mg/l) in mine effluent ponds followed by boreholes (497.2 mg/l) as presented in Fig.26. The value decreased to less than 200 mg/l in river and wells.

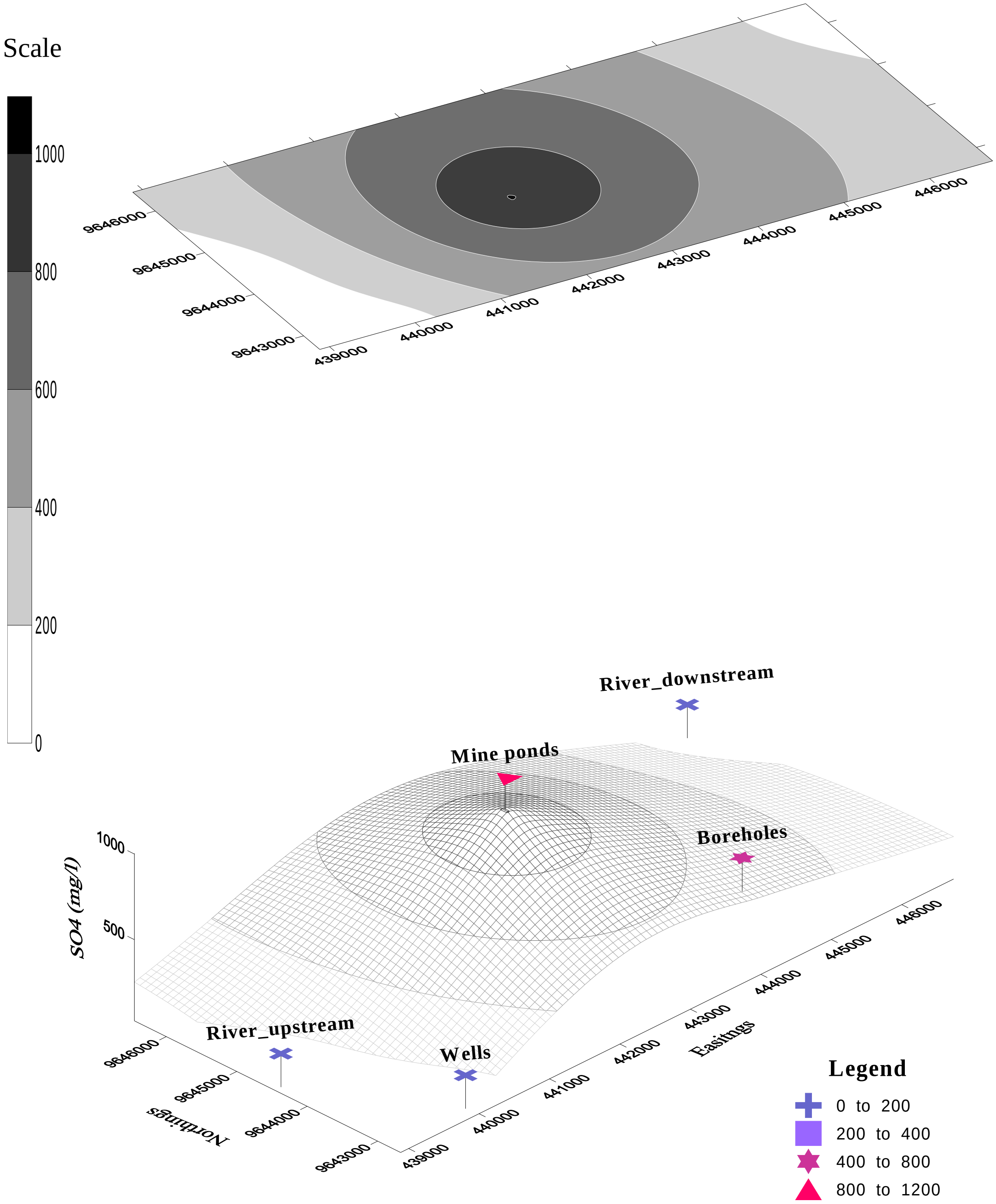


Fig.26. Contour map and DEM showing the mean concentrations of sulphate at different sampling classes for the period of 14th Jan to 17th March 2008.

5.3.4 Spatial distribution of Iron among sites

Fig.27 shows distribution of Fe concentrations in different classes in the study area. The concentration was highest in mine ponds (7.15 mg/l) and downstream the river (4.67 mg/l). The value decreased to 0.22 mg/l in boreholes and wells.

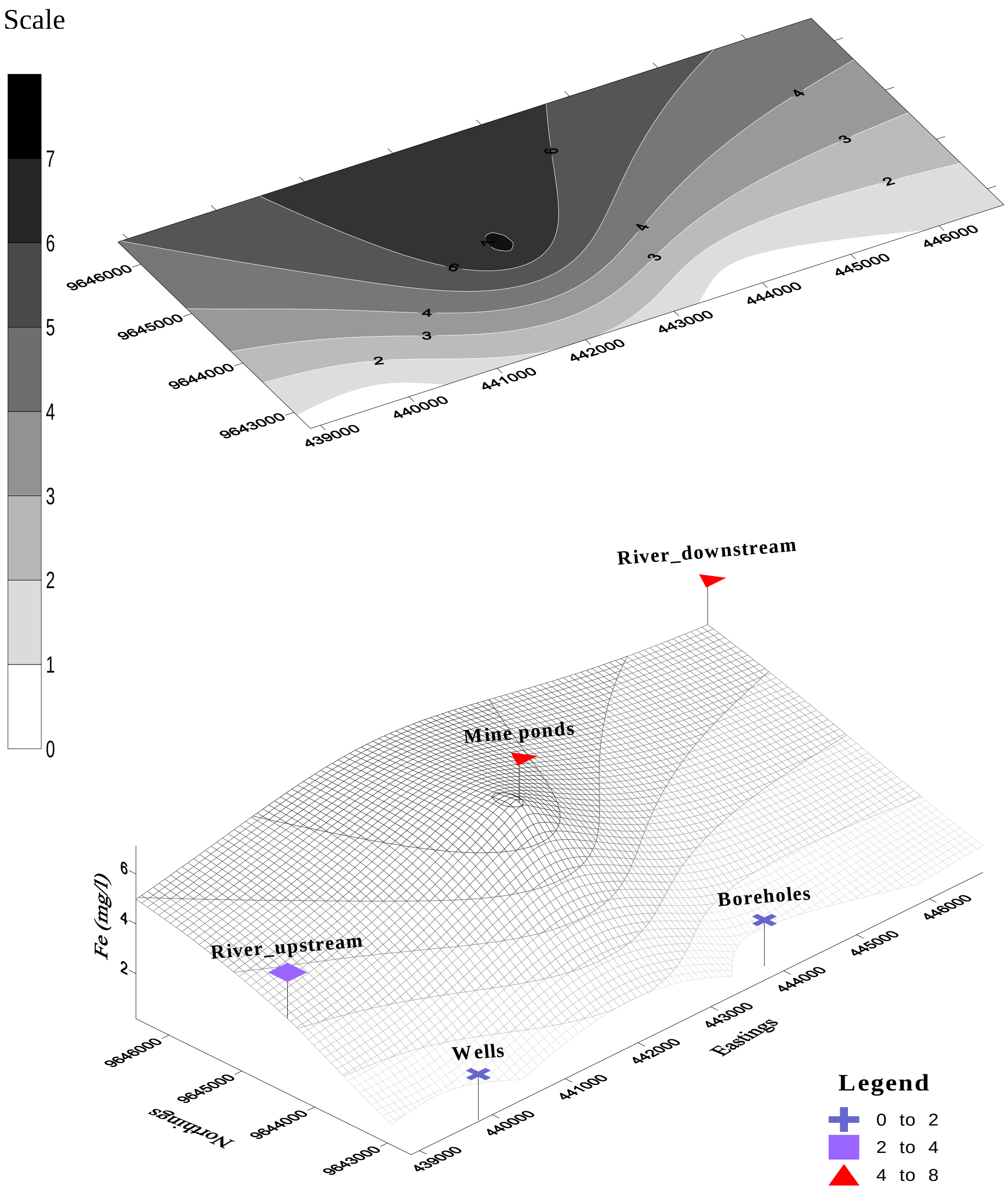


Fig.27. Contour map and DEM showing the mean concentrations of Fe at different sampling classes for the period of 14th Jan to 17th March 2008.

5.3.5 Spatial distribution of Ni among sites

The highest concentration of Ni was observed in mine effluent ponds and river sites where the mean concentrations were 0.74 mg/l and 0.45 mg/l respectively (Fig.28). Low values were observed in wells (0.2 mg/l) and boreholes (0.07 mg/l).

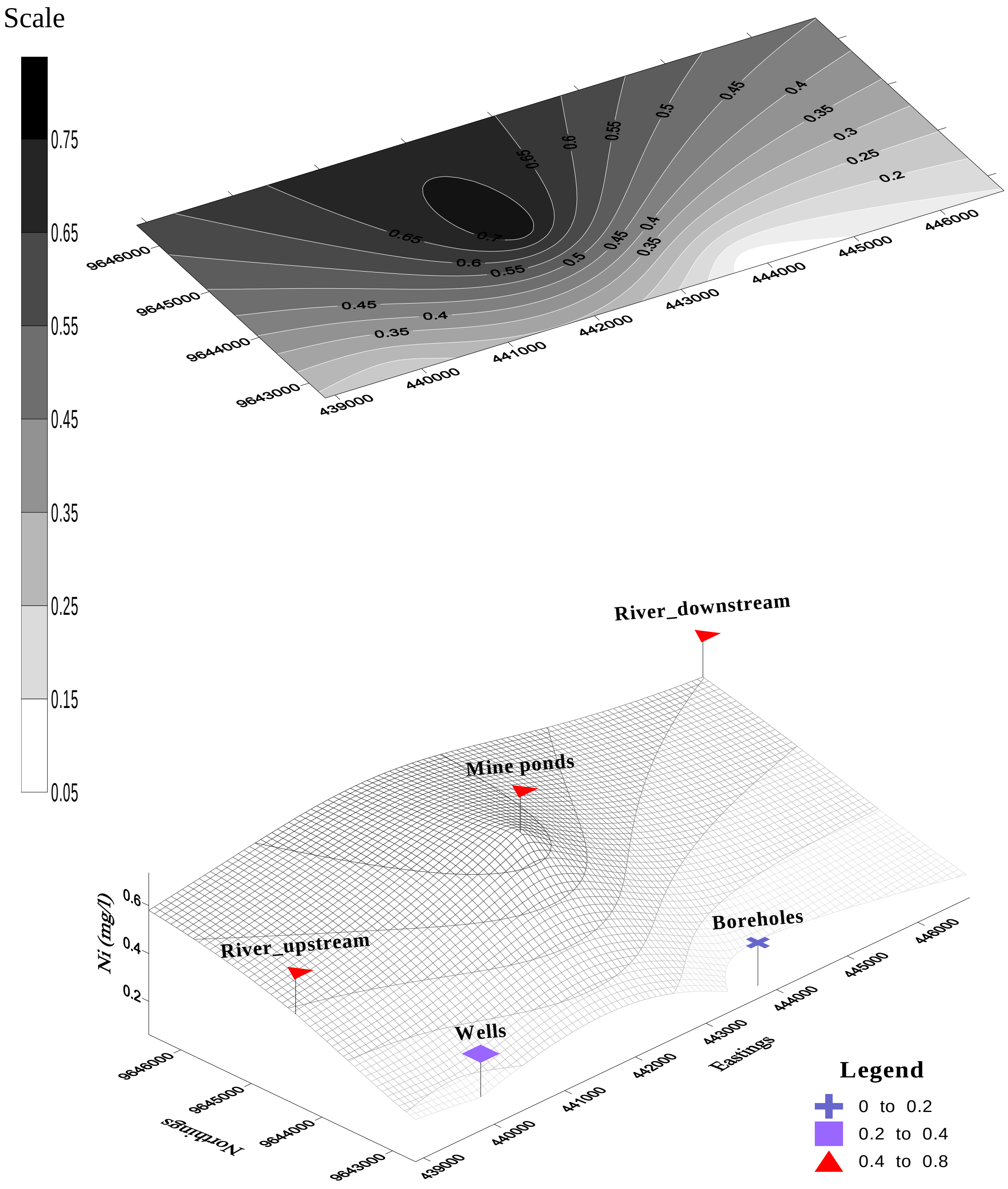


Fig.28. Contour map and DEM showing the mean levels of Ni at different sampling classes for the period of 14th Jan to 17th March 2008.

5.3.6 Spatial distribution of Zinc *among sites*

Highest concentration of Zn (13.04 mg/l) was found in mine effluent ponds, followed by 3.94 mg/l in boreholes. The value decreased to less than 2.5 mg/l in river and wells sites as shown in Fig.29.

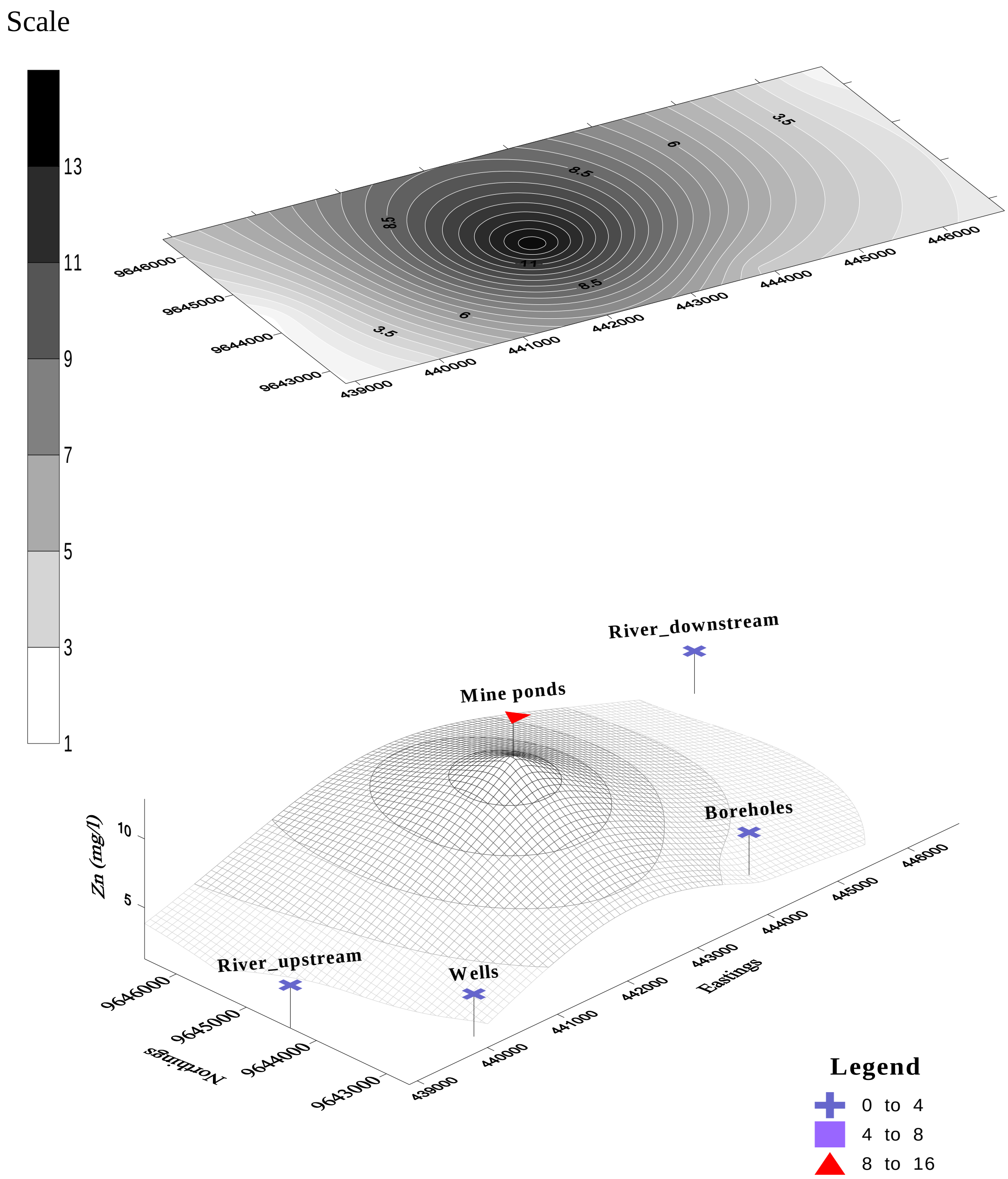


Fig.29. Contour map and DEM showing the mean levels of Zn at different sampling classes for the period of 14th Jan to 17th March 2008.

Concluding remarks for the spatial variation of pollutant among sample classes

From the spatial distribution observation, it was concluded that mine effluent ponds showed highest mean concentrations of most elements studied (heavy metal and non metallic ions), which could be toxic to human health if water is discharged into the river or when people obtain water from boreholes in contaminated area. The river was polluted with respect to Fe and Ni and therefore, not suitable for human consumption. Boreholes appeared to be affected mainly by EC, pH and SO_4^{2+} as for the case of wells only pH seems to affect most.

5.4 BGM water quality monitoring Programme review

A review of the current Bulyanhulu Gold Mine (BGM) surface and groundwater monitoring Programme (mainly groundwater) was done during the research period. BGM had been monitoring surface and groundwater quality since 2001, and had an extensive database of water quality information. However, apart from periodic monitoring reports, which focus on specific contaminants, the data is rarely analyzed for improving water management at BGM. Recommendations based on gaps identified during the monitoring Programme review have been proposed in order to improve their monitoring Programme. Schematic diagram for BGM monitoring boreholes is shown in Appendix 5.

The study designed to review the existing monitoring programme in terms of;

- Monitoring schedule and monitoring network
- Sampling and analytical protocols
- Data quality, storage and interpretation

5.4.1 Monitoring schedule and network

- **Monitoring network**

The current BGM water monitoring network encompassed 21 boreholes (some are not working) and 12 surface water sampling points. Some of the surface water monitoring points were only sampled during overflow or storm events or when they contain water (e.g. trenches and borrow-pits).

The following important shortcomings were identified in the BGM monitoring network thus far:

- There were significant areas in which no boreholes were drilled, where no monitoring data could be obtained (e.g. north and south of the tailings storage facility (Appendix 5),
- In some boreholes especially Plant Site Monitoring Borehole 7 (PMB7). The concentrations of pollutants i.e. SO_4^{2+}, EC and TDS had gradually increased over time. However, there was no down gradient borehole available to see how much further the plume has moved and if it has progressed off site (Fig.30),
- The numbers of monitoring boreholes within the monitoring network were too little, but the sampling intervals (monthly) and list of parameters to be analyzed were too many. This had resulted in large amount of data, which had not been appropriately analyzed and interpreted.
- Receptors like community wells adjacent to the mine were not routinely sampled to check for contamination. Only 3 monitoring boreholes were used for the purposes of understanding the mines impact beyond its borders.

The monitoring borehole with data showing a strong upward trend of contamination at plant site monitoring borehole 7 (PMB7) is shown in Fig.30. The long term trend plotted from water quality data from borehole PMB7 indicated the interrelationship of between TDS, EC and SO_4^{2+}. Clearly it showed how contamination has increased in the borehole since 2004, and indicated that the contamination plume has moved beyond this point and an additional monitoring borehole would be needed down gradient of this location.

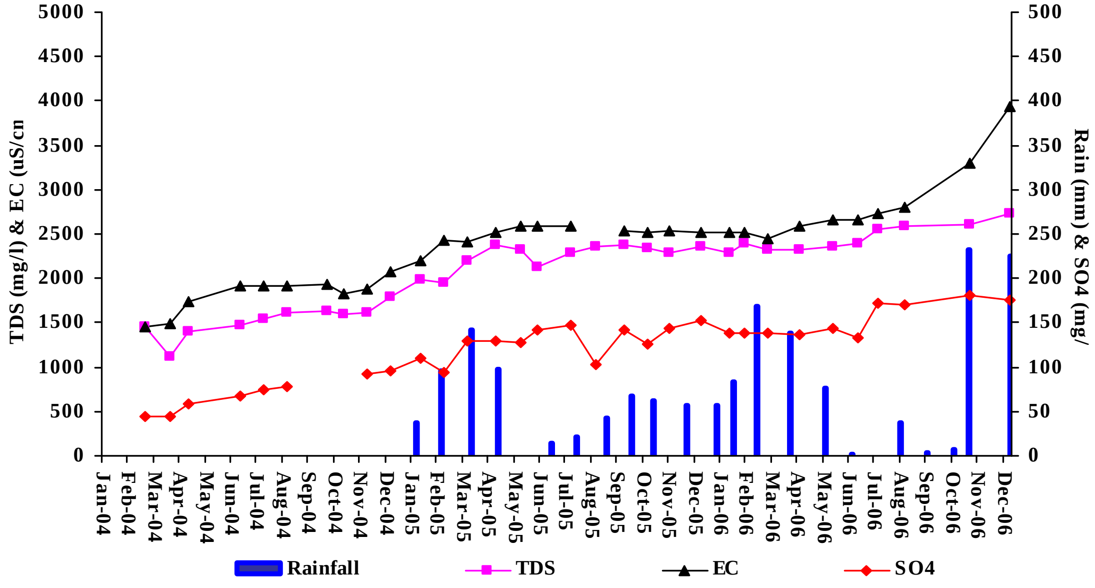


Fig.30. Borehole with data showing a strong upward trend of contamination at PMB7 for the period of Jan 2004 - Dec 2006.

There were also boreholes with a lot of reliable data in the mine showing little contamination, fore instance, Fig.31 indicated the borehole with little contamination at plant site monitoring borehole 3 (PMB3) as compared to PMB7.

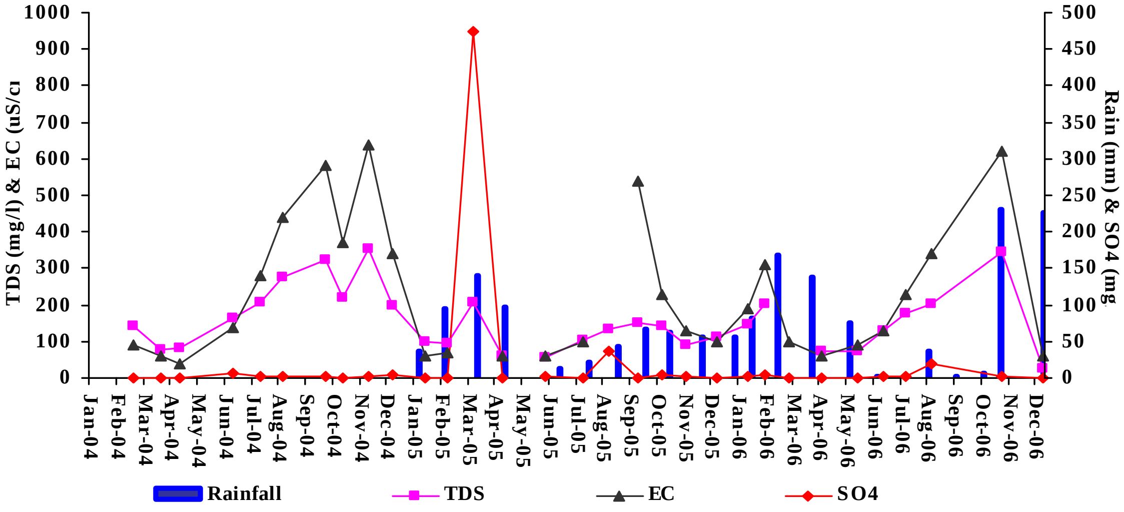


Fig.31. Borehole with good data showing a little contamination at PMB3 for the period of Jan 2004 - Dec 2006.

The recommendation in this situation was to significantly increase the monitoring intervals to at least on a quarterly basis. These intervals could always be reduced again if levels of contamination increase significantly. The link between pH and contamination from metals was also established. Fig.32 showed the borehole with the presence of high levels of Fe contamination.

The borehole (Fig.32) was a good example of the link between pH and contamination from metals at plant site monitoring borehole 3 (PMB3). Low pH results in the dissolution and mobilization of metals in water. That was when the pH was low the metal concentrations increased, especially in this case the Fe concentration. It should be noted however, that with the possible exception of Zn, none of the other metals were present in significant quantities. It was therefore, strongly recommended that the monitoring intervals be increased (i.e. quarterly) and consideration given was to remove some of metals (e.g. Cr, Cd etc) from the list of analytes especially if they are consistently below the laboratory detection limits and prescribed guidelines for water quality. The decision could always be reviewed if the pH conditions in the borehole change substantially.

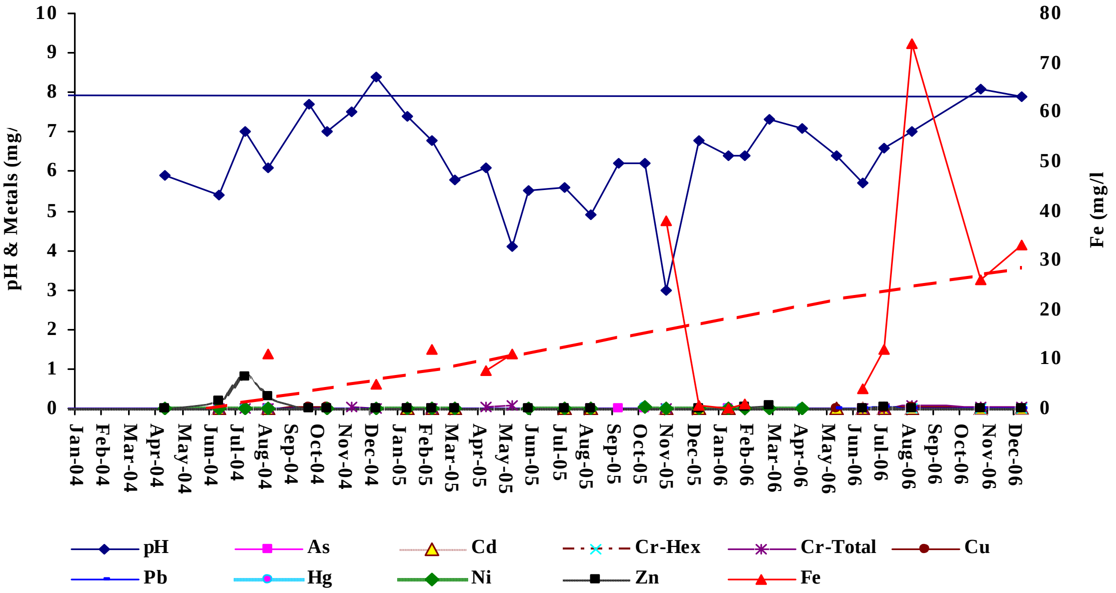


Fig.32. Borehole with data showing presence of Fe contamination at PMB3 for the period of Jan 2004 - Dec 2006.

- **Monitoring Schedule**

The monitoring schedule has been dictated by the sampling operating procedure water monitoring Programme (SOP 48). This specifies which monitoring points are to be sampled when and what analyzes should be undertaken for that sample. The main objectives of the BGM monitoring Programme as detailed in the Environmental Management Plan (EMP) of 1999, is that water quality monitoring is to confirm that the mine is negatively impacting surface and groundwater quality.

The important part of the EMP clause pertaining to both surface and groundwater monitoring is that when a full year of monitoring data are available, consideration would be given in modifying the sampling program frequency when the data demonstrate water quality changes are not occurring or are occurring only very slowly, and if parameter concentrations are not meeting the required guidelines for different water uses. To date this appears not to have been done and as a result many years of expensive data have been accumulated.

5.4.2 Sampling and analytical protocol

- **Sampling protocol**

A good sampling protocol is essential in order to obtain important water chemistry data. Current field protocol describing water sampling procedure (i.e. SOP 48) is detailed and well developed and includes details responsibilities of individuals, monitoring schedule, field procedures, sampling protocols, water level measurement, sample transport and data entry into database.

Two minor improvements to this document was recommended, which were; simpler policy on duplicate/split sampling procedure (i.e. 1 duplicate per sample batch and more importantly how the duplicate sample is used for QA/QC and responsibility needs to be outlined for suitably qualified person to analyse the data on its return from the laboratory and also to establish water quality trends. Obtaining representative, comparable samples is about consistency, and if at all possible, sampling should be performed by the same people and task observations should be held on a regular basis .

- **Laboratory Protocol**

All samples collected at the Bulyanhulu Gold Mine (BGM) were analysed at either the Anglo American Research Lab (AARL) in South Africa or the BGM onsite laboratory. Currently all routine samples are sent to these laboratories and the results from both laboratories were closely related. Informal samples are sent to the BGM laboratory and routine samples to the AARL for the purpose of comparing the BGM laboratory performance against AARL's.

5.4.3 Data quality, storage and interpretation

- **Data quality**

A large quantity of data had been collected since monitoring records began in 2002. This data has the potential to be used to understand the pathways of contaminant movement, and the behavior of contaminants in surface and groundwater. Assessing the comparison between TDS and EC values performed a basic assessment of data quality. The relationship between EC and TDS is illustrated in Fig.33. A strong correlation was expected between these two variables because they are measuring the same parameter. TDS and EC were observed to be closely related. Sulphates and TDS concentrations also had similar trends.

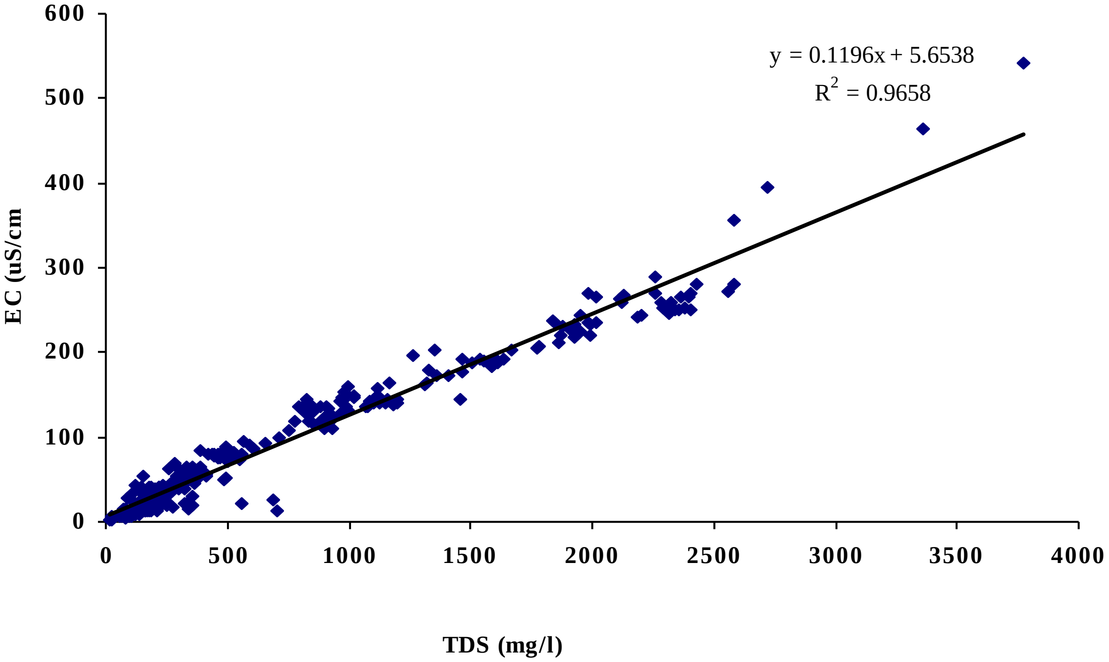


Fig.33. Relationship between EC and TDS at BGM (Jan 2004 - Dec 2006).

- **Data storage and interpretation**

BGM currently uses the EQWin databasing software to store all the water quality data. Data stored in the database include; monitoring point coordinates, water quality standards and guidelines, water chemistry data for both surface and groundwater monitoring points and water levels. This software had only one license on the mine, which severely limits access to the data. However, this software was good for what is intended to be and that is basically a data storage mechanism with fair reporting and graphing functionality. Ideal software for this application should have some of the following characteristics:

- Spatial representation of the data and understand contaminant movement (i.e. possible interface with GIS).
- Be accessible to anyone on the mine, so they can query the data possibly with different levels of access.

On the whole, BGM had an excellent water quality database that is managed sufficiently well at the time of the study. However, through the detailed analysis of the water quality trends significant improvements and cost savings can be made to the water monitoring program. The two main ones include substantial reduction in the list of chemical analytes, especially certain metals, and an increase in the monitoring intervals at most locations from monthly to quarterly and even biannually.

CHAPTER SIX

6. RECOMMENDATION AND CONCLUSIONS

6.1 Conclusions

From the results and analysis, it was concluded that;

- The potential pollutant sources identified at Bulyanhulu Gold Mine (BGM) were; gold process plant, tailing storage facility, Effluent Control Ponds and waste rock dump. The surface water quality of Bulyanhulu River was affected by mining activities with respect to Ni (0.4 ± 0.3 mg/l), Fe (2.9 ± 0.13 mg/l) and slightly by Zn (1.8 ± 0.8 mg/l), which make it unsuitable for human consumption. However, it was also important to note that the mining activities were not the only source of pollution in river as some of the contaminants were detected upstream of the mine. Groundwater quality of boreholes was affected with regard to EC (1023 ± 497 μS/cm), pH (5.9 ± 0.4), SO_4^{2+} (497 ± 205 mg/l), Ni (0.04 ± 0.03 mg/l) and Zn (4.0 ± 2.0 mg/l). As for the case of wells only pH (5.2 ± 0.3) and Ni (0.2 ± 0.1 mg/l) seemed to affect most. The concentration values of Ag, As, Hg, CN^- and NO_3^- were generally low (below method detection limits).

- The quantification of indicative potential pollution loads revealed that the pollutant loads downstream of the river close to mine discharge point were high and decreased far downstream. Effluent ponds showed relatively high loads.

- From the spatial distributions plotted, it was observed that mine effluent ponds had the highest mean concentrations of all heavy metal and non metallic ions studied, this lead to the inference that the mine was potentially impacting the water sources since the levels were found to be high, which could be toxic to human health if water was discharged into the river or when people obtain water from boreholes adjacent to these Effluent Control Ponds in contaminated area.

- BGM monitoring Programme review revealed the following shortcomings;
  - BGM had an excellent water quality database that is managed sufficiently well. However, through the detailed analysis of the water quality trends significant improvements for cost savings was needed.
  - There were significant areas in which no boreholes were drilled thus no monitoring data could be obtained.
  - In some boreholes the levels of pollutants had gradually increased over time and there was no down gradient borehole available to see how much further the plume had moved and if it had progressed off site.
  - Monitoring boreholes within the monitoring network were too little, but the sampling intervals and list of analyzed parameters were too many.
  - Community wells adjacent to the mine were not routinely sampled to check for contamination.

6.2 Recommendations

Based on the results of this study the following recommendations could be made for future consideration;

- It is recommended to treat the effluent of the control ponds by precipitating out metals, thus reducing their mobility through seepage. Additionally, the construction of additional ponds with adequate retention times that can enhance the removal and retention of metals was advised, so that the effluent from the ponds can leave with low concentrations of metal solids.

- The Effluent Control Ponds affected by acid mine drainage and low pH because of weathering of sulphides, liming techniques and caustic soda could be employed to neutralize the drainage and avoid release of pollutants from the sulphides.

- Further research should be conducted in both seasons wet and dry to obtain more information pertaining to heavy metals and other parameters in many groundwater boreholes and surface water samples within the study area, so as to determine the effect of seasonality.

- In order to improve the groundwater monitoring network at BGM, the approach recommended was to develop a detailed conceptual site model (CSM) for the mine lease area, this would require drilling of boreholes in areas where no boreholes and once the CSM is developed, it would be possible to reduce the number of boreholes monitored to only those that would supplying useful and relevant information to the program. Substantial reduction in the list of chemical analytes and an increase of the monitoring interval was also recommended.

- The study highlights some pollutants which may hinder the achievement of Millenium Development Goals, namely **"water for all** by 2015". The statement integrates all of IWRM principles. It was therefore, recommended that miners are educated on the effects of heavy metal pollution in relation to the national poverty relief strategy goals. This contributes to the MDG "environmental sustainability" and the National Strategy for Growth and Reduction of Poverty (NDGRP) .

- The mine should ensure that there is zero discharge of contaminated water emanating from the mining site to the surface water environment

- The study on species diversity is recommended in the study area to determine the different tolerance levels of aquatic species found into the river. The river had shown high concentrations of most pollutants studied, which could be toxic to aquatic species.

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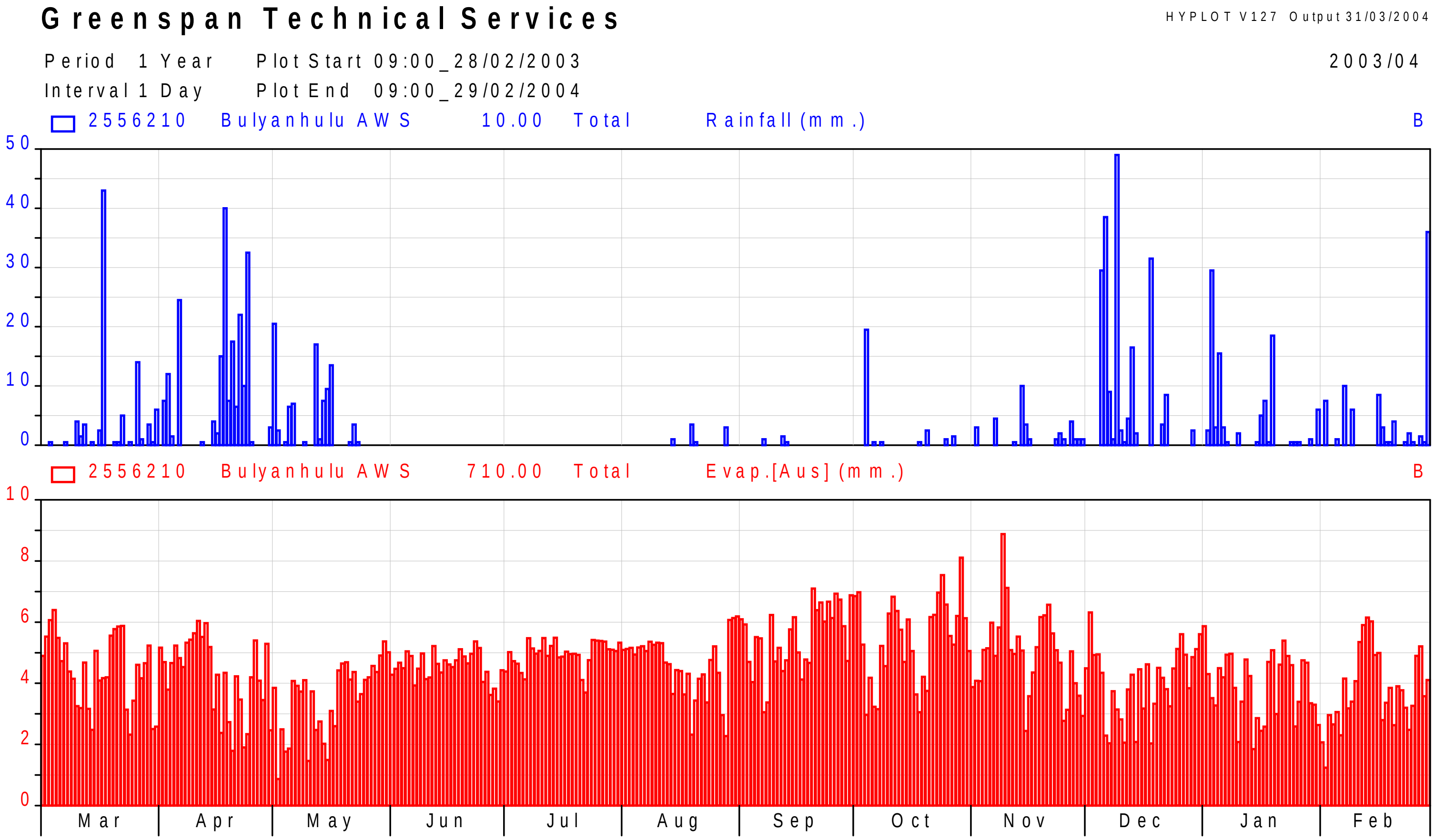
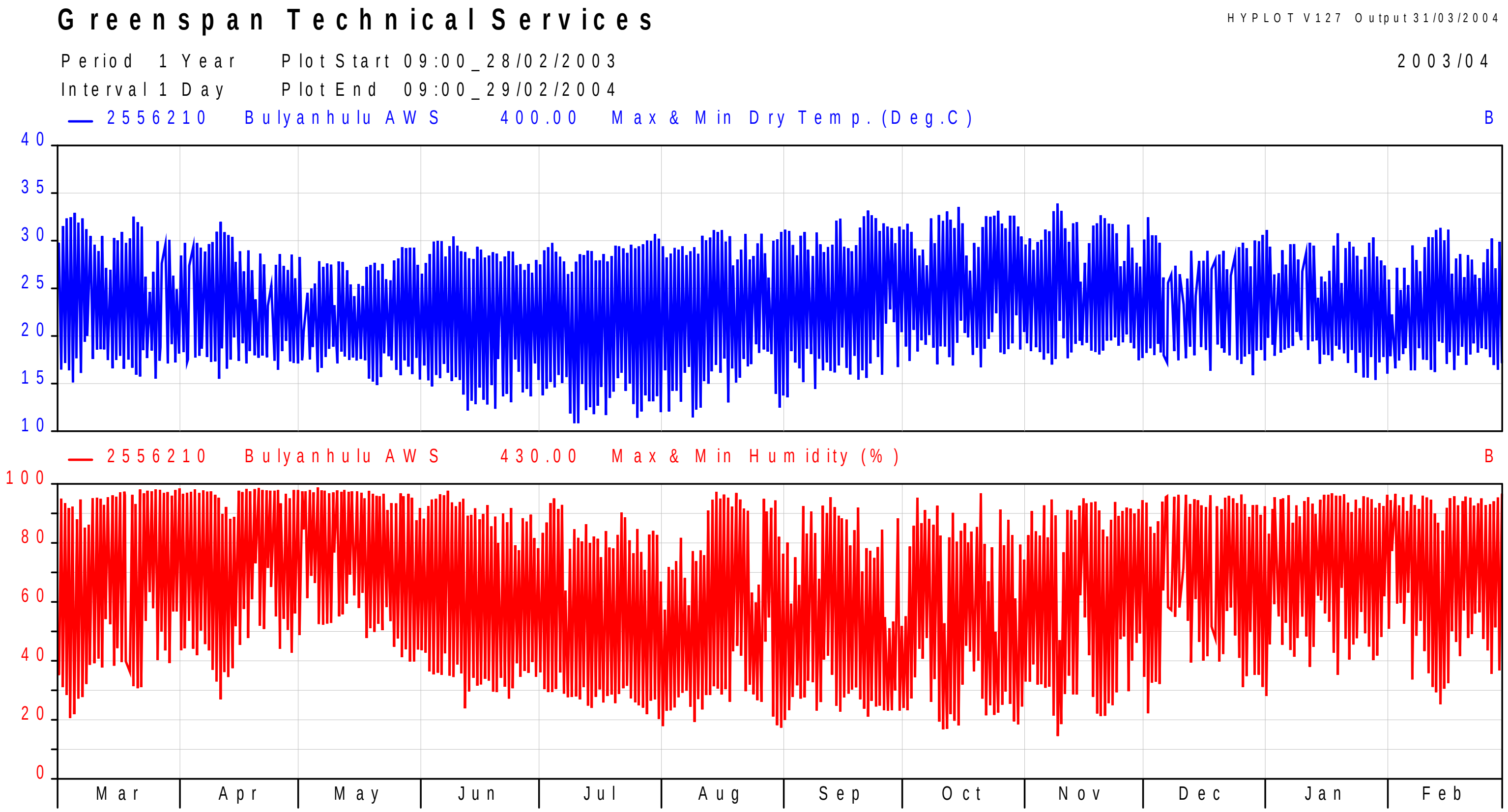
APPENDIX I: Annual Rainfall and Evaporation at BGM (2003/2004)



(Source: Malunga, 2007)

APPENDIX II: Annual Temperature and Humidity at BGM (2003/2004)

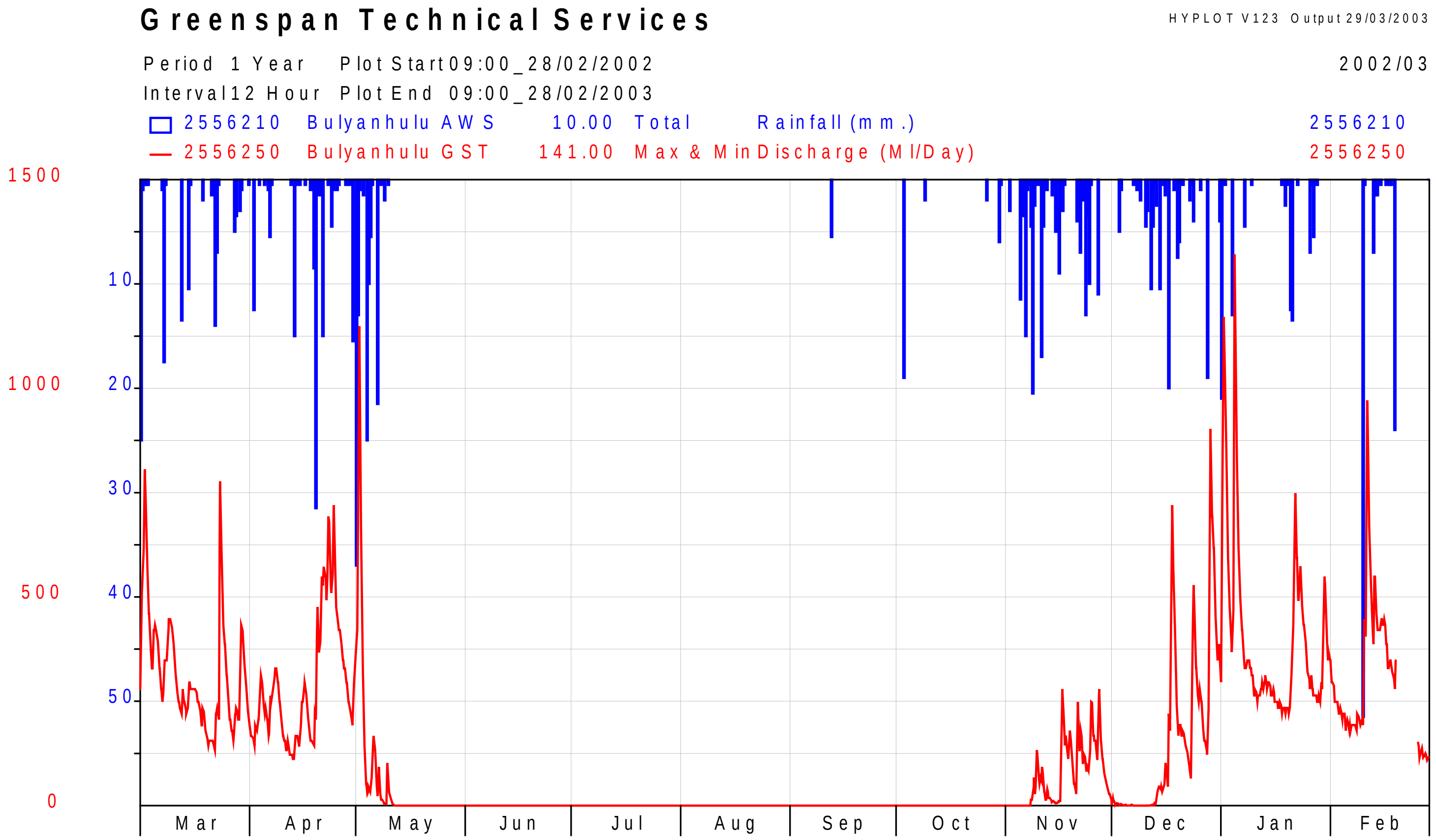


(Source: Malunga, 2007)

APPENDIX III: Tailings Effluent Control Pond (TDRP) lined with a synthetic plastic liner at Bulyanhulu Gold Mine (BGM).

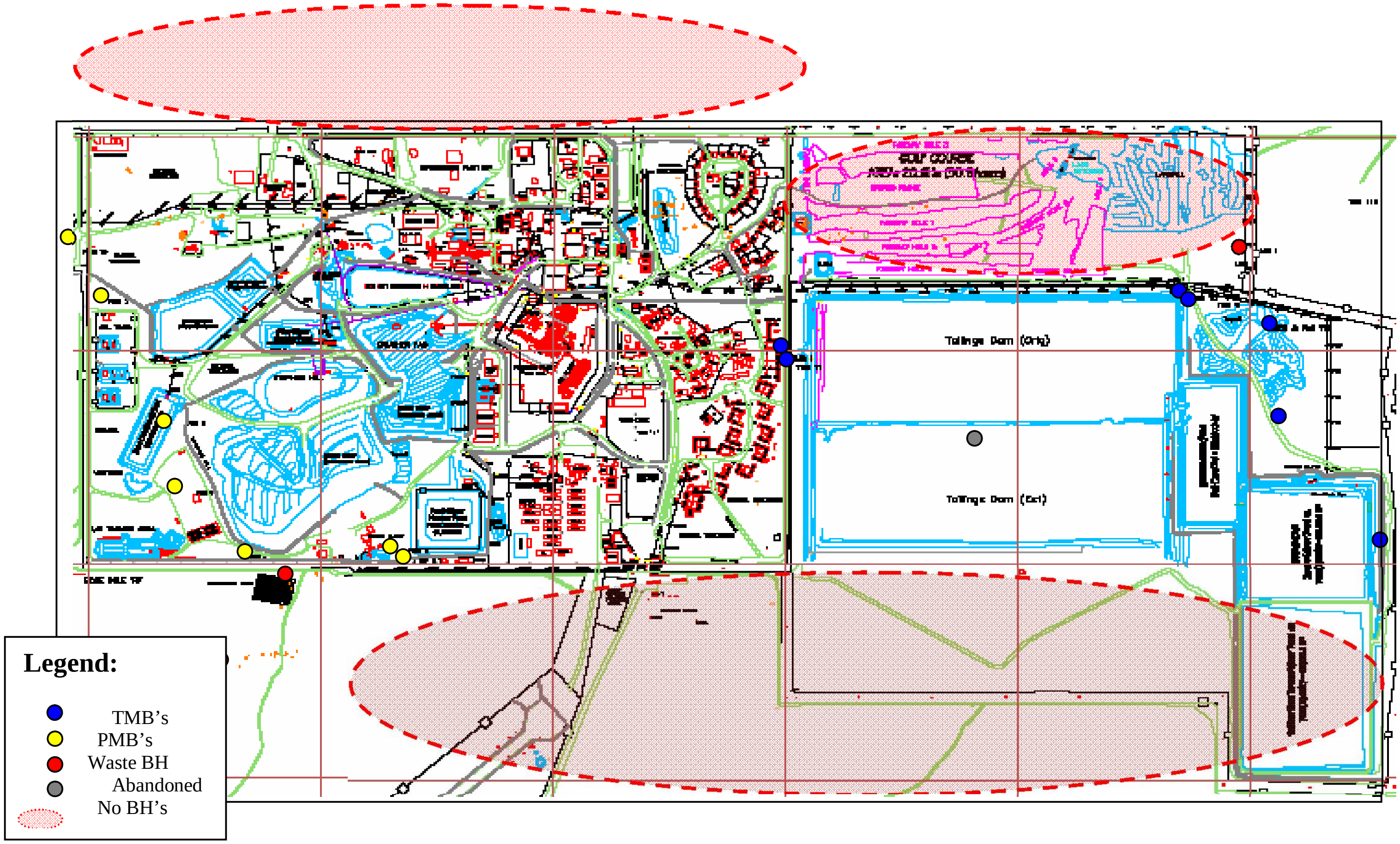
Tailing effluent control pond (TDRP) lined with HDPE plastic liner

APPENDIX IV: Bulyanhulu GST - Annual Flow and Rainfall Graph



(Source: Malunga, 2007)

APPENDIX V: Schematic layout of Plant Site and Monitoring Boreholes at BGM



Note: TMB's = Tailings side monitoring boreholes, PMB's = Plant side monitoring boreholes and Waste BH = Waste boreholes (domestic waste).