# UNIVERSITY OF BOTSWANA


**DEPARTMENT OF GEOLOGY**

# IMPACTS OF TREATED WASTEWATER ON THE SURFACE WATER AND GROUNDWATER QUALITY: A CASE STUDY IN NORTH EAST GABORONE (WITHIN NOTWANE CATCHMENT), BOTSWANA

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# ABSTRACT

This study was conducted in the Notwane catchment where the capital city of Botswana, Gaborone is located. Botswana having unreliable rainfalls and Gaborone having shortage supply of water for drinking, this study was initiated with the aim of investigating alternative sources of water in this part of the country. Even though treated wastewater is available in the studied area, this water is not much utilized at present. The objective of the research is to investigate the impact of treated wastewater on the quality of surface water and groundwater in the north east of Gaborone, so that this water can be utilized for different purposes including as a source for groundwater recharge. The research area is located near Gaborone in south east district within Notwane catchment, which is a tributary to the Limpopo River, having an area of about 3 000 sq. kms. For this purpose forty-one surface water samples, one treated waste water sample and fifteen groundwater samples were collected from different parts of the study area. All the water samples were analysed for major cations ($Ca^{2+}$, $Mg^{2+}$, $K^{+}$, $Na^{+}$ and $Li^{+}$), anions ($HCO_3^{-}$, $Cl^{-}$, $SO_4^{2-}$, $NO_3^{-}$, $F^{-}$, $PO_4^{3-}$ and $CO_3^{2-}$ ) and some trace elements (As, Ba, Cd, Co, Cr, Cu, Fe, Mn, Pb, Ni and Zn). The major cations and all the trace elements were analyzed in the geochemistry laboratory of the Department of Geology, University of Botswana using Inductively Coupled Plasma Mass Spectrometry or ICP-MS. The anions were analyzed in the water quality laboratory of the Department of Water Affairs. For all the water samples alkalinity and hardness were determined using AquaChem software. Simple descriptive statistical method was utilized for the analyses of the water chemistry data. AquaChem and Suffer software's were also used for analyses the water chemistry data. The surface water is slightly alkaline to alkaline, fresh, soft to very hard whereas the treated wastewater is slightly alkaline, fresh and hard. Groundwater is slightly acidic to alkaline, fresh to saline and soft to very hard. In all the waters, surface water, treated wastewater and groundwater based on the mean values of the chemical parameters, the cations were in the order of abundance as $Na^{+} > Ca^{2+} > Mg^{2+} > K^{+} > Li^{+}$. Surface water anions were in the order of abundance as $HCO_3^{-} > Cl^{-} > SO_4^{2-} > NO_3^{-} > PO_4^{3-} > F^{-} > CO_3^{2-}$, treated wastewater as $HCO_3^{-} > Cl^{-} > NO_3^{-} > SO_4^{2-} > PO_4^{3-} > F^{-} > CO_3^{2-}$ while in the ground water the anions reveal order of abundance as $Cl^{-} > HCO_3^{-} > SO_4^{2-} > NO_3^{-} > CO_3^{2-} > F^{-} > PO_4^{3-}$. Based on the mean values of the chemical parameters in the surface water, the analyzed trace elements were in the order of abundance as Ni > Fe > Pb > Ba > Zn > Mn > Cd > As > Co > Cr > Cu, in the treated water Ni > Ba > Zn > Pb > Fe > Cd > Mn > As > Co > Cr and Cu having equal concentration (0 mg/l) while in the groundwater the analyzed trace element reveal

order of abundance as Ni > Pb > Ba > Mn > Zn > Fe > Cd > As > Cu > Co > Cr. The results of the hydrochemical analyses of all the waters disclose that the groundwater chemistry is highly controlled by rock-water interaction and anthropogenic activities in the catchment than the chemistry of surface water and treated wastewater. The analysed cations for surface water and treated wastewater satisfy the standard of both WHO and Botswana Bureau of Standards whereas in the groundwater the cations are highly above the recommended limits of the standards set by both WHO and Botswana Bureau of Standards with the exception of lithium and potassium. The analysed anions for surface water and treated wastewater fulfil the standard of both WHO and Botswana Bureau of Standards whereas in the groundwater the concentration of Cl and $NO_3$ were above the standards set by both WHO and Botswana Bureau of Standards. In the analysed trace elements for all the waters, almost all samples met the trace element standards set by both WHO and Botswana Bureau of Standards with the exception of nickel and lead in surface water, treated wastewater and groundwater. The overall chemical analyses of the water chemistry revealed that treated wastewater quality does not have any significant harm to both surface and groundwater quality; therefore it can be used as a source of recharge to the aquifers in the catchment.

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## ACRONYMS

**BOBS** Botswana Bureau of Standards

**$CaSO_4.2H_2$** gypsum

**Cl** Chloride

**$CO_2$** carbon dioxide

**Cu** Copper

**Cr** Chromium

**EC** Electrical conductivity

**$H_2CO_3$** carbonic acid

**$HCO_3$** Bicarbonate

**Fe+3** Ferric

**Fe** Iron

**GIS** Geographic Information System

**Mn** Manganese

**Ni** Nickel

**$NO_3$** Nitrate

**PSQCA** Pakistan Standard Quality Control Authority

**Pb** Lead

**$SO_4$** Sulphate

**TDS** Total dissolved solids

**TH** Total hardness

**TOC** total organic carbon

**WHO** World Health Organization

**Zn** Zinc

# 1.0 INTRODUCTION

## 1.1 General

Sewage water refers to the water that has biological, physical and chemical contaminants which is generated by resident, institutional and commercial industrial establishment. Water is said to be polluted when it contains enough impurities to make it unfit for a particular use, such as drinking, swimming, or fishing. Sewage water treatment refers to the process of reducing the contaminants to acceptable levels to make the water safe for discharge back into the environment and reuse for irrigation, washing, construction and many more. It includes the physical, biological and chemical processes to remove physical chemical and biological contaminants.

Physical treatment is the application of physical processes such as sieving (screening) to remove solid materials that did not dissolve in the waste water. Biological treatment involves the use of micro-organisms to treat wastewater. The settled wastewater is introduced into a specially designed bio-reactor where under aerobic or anaerobic conditions the organic matter is utilized by micro-organisms such as bacteria (aerobically or anaerobically), algae, and fungi (aerobically) (Samer, 2015). Chemical process involves the use of chemicals where reactions cause precipitation, neutralization, adsorption, disinfection (chlorine, ozone, ultraviolet light), and ion exchange to treat waste-water to a reusable standard.

The general sewage (wastewater) treatment involves four stages, screening, primary, secondary and tertiary treatment.

**STAGE ONE: Screening**

Screening is first stage of the wastewater treatment process. Screening removes large objects like diapers, nappies, sanitary items, cotton buds, face wipes, broken bottles, bottle tops, plastics and rags that may block or damage equipment. Special equipment is also used to remove grit that gets washed into the sewer.

**STAGE TWO: Primary treatment**

This involves the separation of organic solid matter (or human waste) from the wastewater. This is done by putting the wastewater into large settlement tanks for the solids to sink to the bottom

of the tank. The settled solids are called ‘sludge’. At the bottom of these circular tanks, large scrappers continuously scrape the floor of the tank and push the sludge towards the centre where it is pumped away for further treatment. The rest of the water is then moved to the Secondary treatment.

**STAGE THREE: Secondary treatment**

The water, at this stage is put into large rectangular tanks. These are called aeration lanes. Air is pumped into the water to encourage bacteria to breakdown the tiny bits of sludge that escaped the sludge scrapping process.

**STAGE FOUR: Final (tertiary) treatment**

Next the ‘almost’ treated wastewater is passed through a settlement tank. Final treatment (tertiary treatment) may be divided into three main treatment types namely; chemical, physical and irradiation. Physical treatments generally involve one or a combination of treatments such as rapid sand filtration, additional nutrient removal or carbon adsorption which is employed prior to chlorination to remove any remaining suspended solids as well as reduce the amount of nitrates, phosphates and soluble organic matter present. Following this, disinfection by chemical and irradiation may occur and generally involves one or a combination of treatments involving chlorination and ultraviolet light exposure or ozonation, the choice of which depends solely on the incoming effluent quality, ease and cost of installation, maintenance and operation as well as effects on flora, fauna and recreational users from final effluent re-use and disposal into respective receiving water bodies almost free from harmless substances and chemicals (Naidoo & Olaniran, 2013).

Water quality standards are designed to provide us with understanding the critical importance of adequate supplies of clean, available fresh water for the environment, the country’s economy and the quality of life. Botswana Bureau of Standards (BOBS) has established upper limits and ranges for chemical levels allowable in drinking, irrigation and livestock water. Most of these levels allow a sufficient margin of safety. It must be noted that acceptable contaminant levels vary widely among individuals, for example high sodium which may be harmless for many people can be dangerous for elderly, hypertensive persons, pregnant women and people having difficulty in excreting sodium.

Botswana is experiencing shortage of water supply due to prolonged dry seasons and declined rainfall amounts. In support of that the annual has decreased and it was found out that rainfall quantiles with a 10-year recurrence interval will decrease by 2–17%, (Parida & Moalafhi, 2008). According to Botswana Central Statistics Office (2009) water from dams and rivers contribute about one third to national water consumption. An increasingly large proportion of the population which resides in the urban areas as a result of urban migration is supplied by water from the dams. Gaborone dam supplies water to two towns: Gaborone and Lobatse. The dam is located along Notwane River and has a storage capacity of 141.1 million cubic meters. Its water is supplemented by Bokaa dam located along the Metsimotlhabe River in Kgatleng District.

According to statistics Botswana (2011) the population of Gaborone has increased from 186 007 in year 2001 to 231 592 in 2011 and forecasted an increase to 259 300 in 2016 which directly also indicate an increment in the water demand. Statistics also indicated that Gaborone uses about 2 824 291* $10^3$ litter of water monthly. The high water demand in southern parts of Botswana prompted the operation of North South Carrier (NSC) pipeline that supplies water from Dikgathong Dam in the Northern part of Botswana, to Gaborone and surroundings in the southern part of the country. Furthermore Botswana Ministry of Minerals Energy Water Resources (2015) revealed that there was high reliance on the North South Carrier (NSC) that seemed to operate at maximum capacity. Water transferred through the NSC between 2012/13 and 2013/14 has increased and amounts to 23.6 and 36.1 million cubic meter, respectively, in the given period and that has brought water conservation strategies and reuse into consideration.

Treated wastewater became an alternative and reduced the reliance on fresh water for purposes such as irrigation and construction. In the study area the wastewater treatment plant is located on latitude $24.61^0$S and longitude $25.96^0$E in Glen Valley (Gaborone North-east), downstream of Gaborone Dam. The first phase of a treatment works has a capacity of 40,000 $m^3$/day and operating at an average of 20 000 $m^3$/day. The second face of the plant has a capacity of 50 000 $m^3$/day and has not started operating which totals to 90000 $m^3$/day if the plant operates at 100%. The treatment plant is expected to treat all the wastewater generated in the greater Gaborone and it also has an emergency overflow sewage-retaining dam. After treatment the water is pumped to maturation ponds that are situated near Phakalane. The ponds allow the water for further treatment as the water stays there for 15 days before it can be discharged into Game Park. The

water from the maturation converges at the pump station where it pumped to existing reservoirs where it is utilised for various purposes such as irrigation and construction. The water in the ponds is also a source of aquatic life, birds, other animals and beautiful reeds. Furthermore, the area near the ponds slopes to the Notwane River, which is the main stream in the catchment. Water resources of the study area are dominated by the Notwane River that flow downstream of Gaborone dam and treated wastewater from wastewater treatment plant, which also flows to the Notwane river.

Two of the fundamental controls on water chemistry in drainage basins are the type of geologic materials that are present and the length of time that water is in contact with those materials. Chemical reactions that affect the biological and geochemical characteristics of a basin include acid-base reactions (Lower, 1996), precipitation and dissolution of minerals (Spence & Telmer, 2005), sorption and ion exchange (Kadirvelu & Goel, 2005), oxidation-reduction reactions (Jensen, 2009), biodegradation, dissolution and exsolution of gases. When water first infiltrates the land surface, microorganisms in the soil have a significant effect on the evolution of water chemistry. Organic matter in soils is degraded by microbes, producing high concentrations of dissolved carbon dioxide ($CO_2$). This process lowers the pH by increasing the carbonic acid ($H_2CO_3$) concentration in the soil water. The production of carbonic acid starts a number of mineral-weathering reactions, which result in bicarbonate ($HCO_3^-$) commonly, being the most abundant anion in the water. Where contact times between water and minerals in shallow groundwater flow paths are short, the dissolved-solids concentration in the water generally is low. In such settings, limited chemical changes take place before groundwater is discharged to surface water (Winter, 1998). Due to its location inside the study area, treated wastewater is also contributing to the chemistry of the natural water of study area on the top of the above mentioned factors.

The impacts of treated sewage water in Gaborone are generally based on sewage water movement on the surface and underground. The greatest threats posed to water resources arise from contamination by bacteria, nitrates, metals, trace quantities of toxic material and salts. Seepage overflow into drinking water sources can cause diseases from ingestion of micro-organisms and heavy metals. According to Emongor & Ramolemana (2004), there are physical and chemical soil related problems associated with using secondary treated sewage water in

horticultural production. The physical problems include clogging, soil drainage and aeration while the chemical problems include soil salinity, sodicity and accumulation of heavy metals. They also concluded that because of secondary treated water there are some problems associated with the effluent water applied to vegetables and fruits. The wastewater irrigated soils in the Glen valley have higher concentration of Cd (≥0.01), Ni (≥0.20), and Cu (≥0.20) than the recommended levels whereas the levels of Hg, Pb and Zn are lower than the maximum threshold values recommended for crop production (Mosime et al., 2011).

Groundwater contamination is a concern in Botswana two well fields, the Ramotswa and the Mochudi well fields, which are located in the south-eastern part of Botswana. The well fields are no longer used for water supply sources for drinking purposes as a result of bacterial and nitrate pollutions caused by poor disposal sanitary waste (Alemaw, 2004). As abstraction rates increases in the wells of these well fields, the cone of depression increases and water would be drawn from far and often interferes with many pollution sources as shown in the figure below.

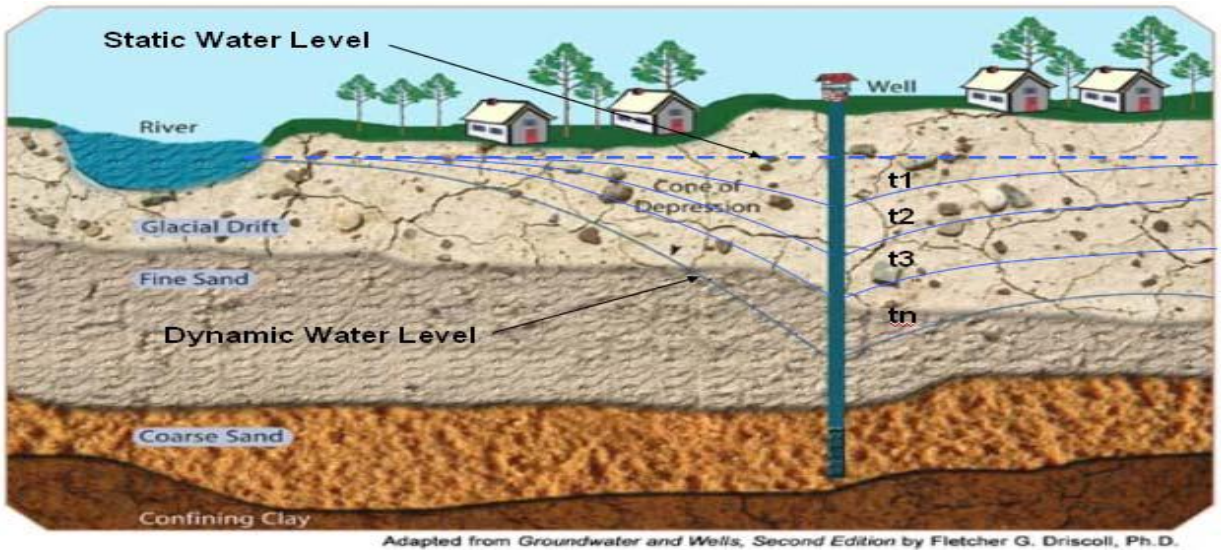


Figure 1. Groundwater system taken from groundwater and wells by Driscoll 1986.

Figure 2 below shows surface water level (treated wastewater) flowing out of Notwane River during dry season (winter when there was no rainfall) measured downstream.

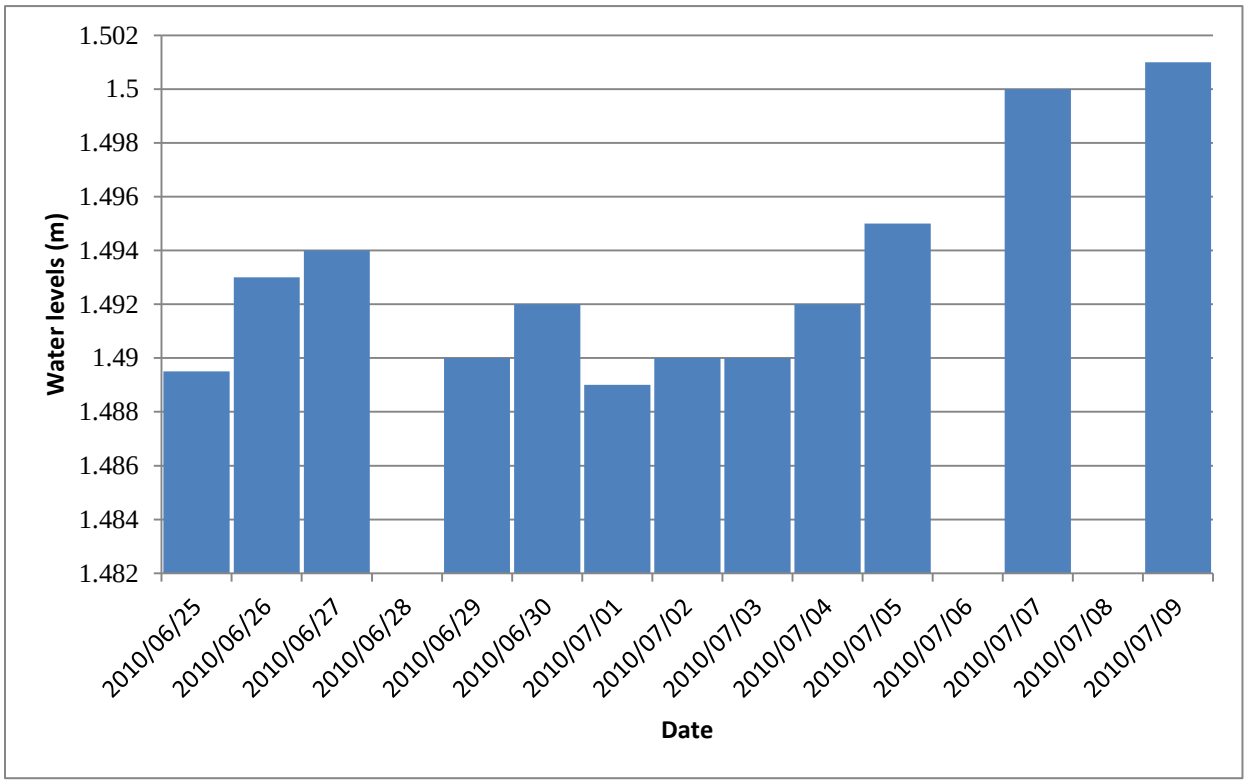


Figure 2. Treated water levels gauge at Mmakgopong in year 2010.

Figure 3 below shows treated wastewater flowing in Notwane River at Mmakgopong during dry season (taken in June 2014), when the only source to the river is the treated wastewater.

Figure 3. Treated wastewater flowing in Notwane River.

## 1.2 Problem Statement

Shortage of water supply in Gaborone is a major problem. Gaborone dam which was the major supply of water in city has failed due to increased water demand and less rainfall. Currently the city is supplemented by Bokaa Dam located along the Metsimotlhabe River in Kgatleng District and North South Carrier (NSC) pipeline that supplies water from the Northern part of Botswana, (Dikgathong Dam) to the south. Groundwater and use of treated wastewater are alternatives source for the future of the city. The use of treated wastewater for different purposes is entirely depending on the degree and type of treatment that the water undergoes. The physical, chemical and biological nature of the treated water should be understood before the water is used for the required purposes. At present the treated wastewater is used for agricultural, cleaning, construction purposes and also a source of aquatic life in the study area. However its impact to the surface water and groundwater has not yet been evaluated. This research was proposed and conducted to fill such gaps.

## 1.3 Objectives

### *1.3.1 General Objective*

The major objective of this research is to investigate the impact of treated wastewater on the quality of surface water and groundwater in the North-east of Gaborone.

### *1.3.2 Specific Objectives*

The following are the specific objectives the research.

- To investigate the major ions and trace element composition of the surface water:
- To investigate the major ions and trace element composition of the groundwater:
- To investigate the major ions and trace element composition of the treated wastewater:
- To investigate the impact of the treated wastewater on the groundwater quality
- To investigate the suitability of the treated wastewater for drinking purpose: and,
- To investigate the suitability of the treated wastewater as a recharge source for the aquifers in the Gaborone area.

## 1.4 Description of the Study Area

### *1.4.1 Location and Accessibility*

The research area is located near Gaborone in south east district bounded between 23.7$^{o}$ S and 24.7$^{o}$ S and 25.8$^{o}$E and 27.0$^{o}$E within Notwane catchment which has a total area of about 18 053 square kilometres. It is bound to the southwest by the Southern District, to the northwest by the Kweneng District and in the north by the Kgatleng District. The entire eastern part of the district borders with South Africa. Hydrologically, the study area is along the Notwane River downstream of the Gaborone dam about 3 000 square kilometres to Mmakgopong village. The Notwane River is a tributary of Limpopo River. The river is easy to access as it passes though Gaborone city and villages like Oodi and Mochudi which has tarred access roads, downstream at Mmakgopong village it can also be accessed by dust roads from the main tarred road (A1) which connects Gaborone city and the city of Francistown.

Figure 4 and 5 shows the location of the study area, which start from the South east (Gaborone city) district into Kgatleng district and the study area boundary in Notwane Catchment.

## LOCATION MAP

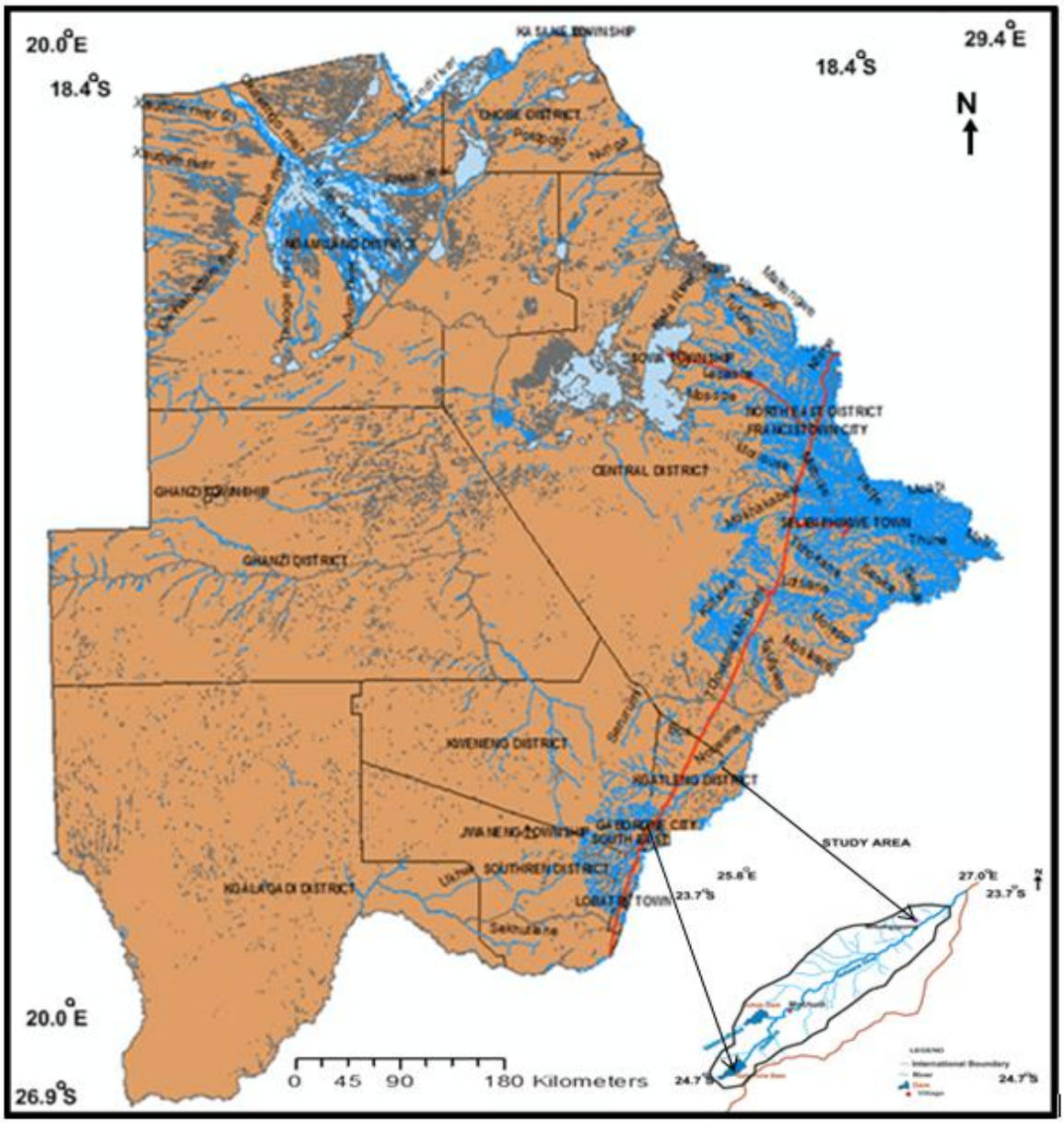


Figure 4. Location map of study area.

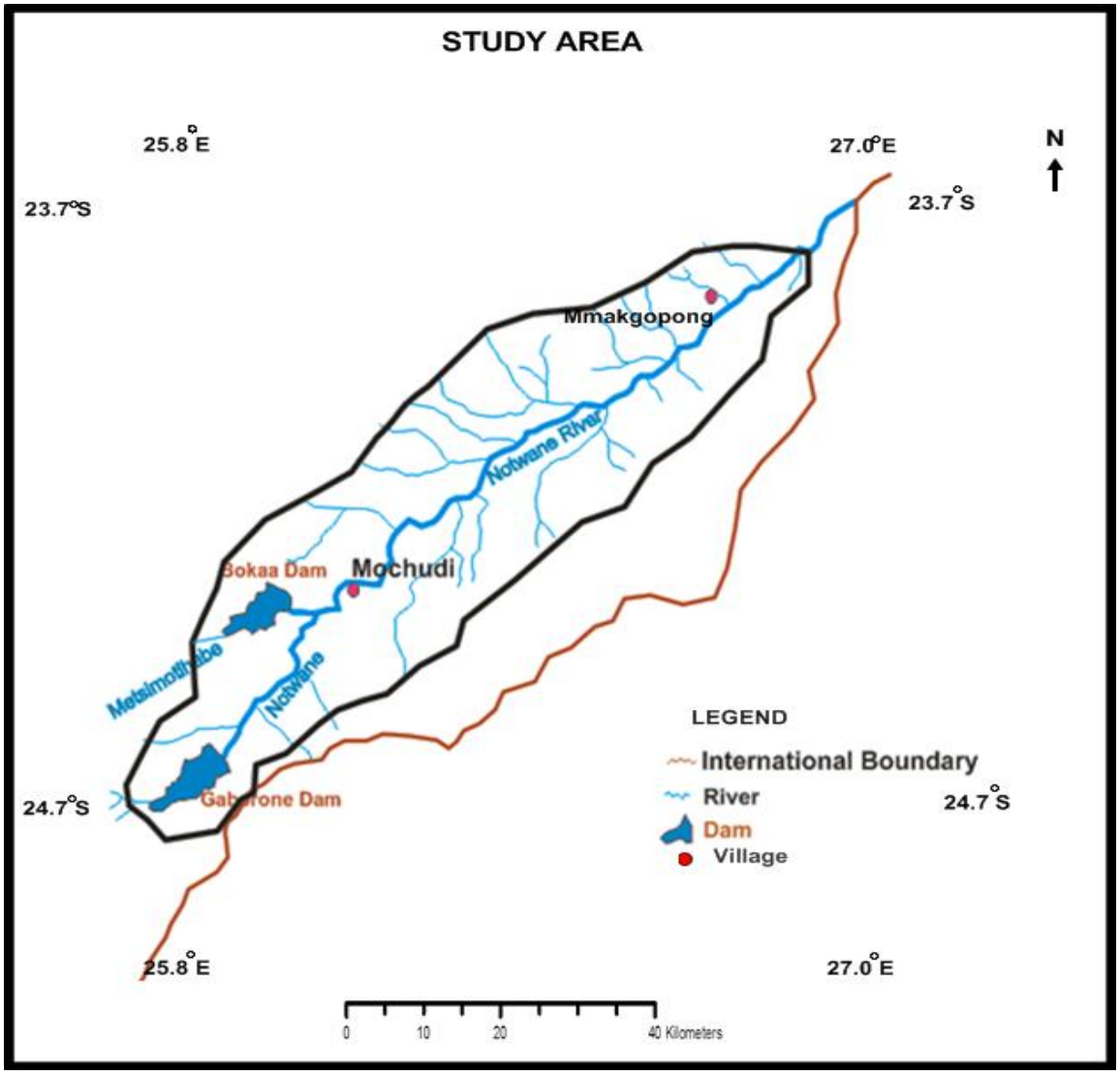


Figure 5. Study area in Notwane catchment.

### *1.4.2 Physiography and Drainage*

The study area is generally undulating with slopes from south-east (upstream) to north-east (downstream). There are notable hills upstream near Gaborone (Kgale Hills) with peak of 1287 metres above sea level. The rivers in the study area are Madikwe and Limpopo which contributes an international boundary with republic of South Africa. The Notwane River drains north - east into the Limpopo River and the water treatment plant is situated in Notwane catchment area. According to the Moganane (1989) the catchment area has tributaries Metsimotlhaba, Thagale and Monametsana rivers. The catchment area form low drainage density patterns, suggesting absence of structural control of surface water flow. The overall drainage pattern of Notwane

River and its tributaries is sub parallel with tributaries joining from west and few and small from east. Also all rivers are deeply inclined and narrow; they have narrow strips of alluvial plains and occasionally some terraces.

### *1.4.3 Climate*

The climate of the study area is generally semi-arid with an annual average rainfall varying between 250-500 mm, unreliable, unevenly distributed and highly variable from year to year and together with a very high amount of evaporation which is of the order of about 2000 mm/annum. Botswana experiences two seasons, summer and winter. "The summer season lasts from October to March and is characterized by high temperatures, generally over 30°C during the day, rising to the low 40°C. Almost all the rainfall for the year happens during this period. The winter season lasts from April to September; nights are cool with occasional frosts, while daytime temperatures are in the mid 20°Cs. There is almost no rainfall during this period" (Jefferis & Nemaorani, 2013).

### *1.4.4 Geology of the area*

The study area lies in the south eastern part of Botswana within the northern margin of the Kaapvaal craton. The south eastern part of Botswana is underlain by Archaean to Mesozoic geologic units (Fig.6) that are covered by recent Quaternary deposits. The Archaean geology covers almost the whole of South-east Botswana, constituting the basement units. The Gaborone Igneous Complex (GIC) which is of Neoarchaean age forms the integral part of the geology of South-east Botswana. It was intruded into the Paleoarchaean gneisses and granitoids which form the basement units in the northern margin of the Kaapvaal craton. The Gaborone Igneous Complex is composed of a multiphase granitic batholith surrounded in part and intruded into rhyolites and volcanoclastics of the Lobatse Group (Carney et al., 1994). The complex can be divided into volcanic and plutonic components with the volcanic component made up by the Kanye Volcanics and the Nnywane Formation of the Lobatse group while the plutonic component is divided into Thamaga Granite, Kgale Granite and the Ntlhantlhe Microgranite (Key, 1982).

The core of the Gaborone Igneous Complex is composed of the Thamaga Granite which is medium-to-coarse grained and displays a rapakivi texture. Thamaga Granite transitions into the Kgale Granite which is an equigranular, homogenous, medium-to-coarse grained, leucocratic

granite. The Ntlhantlhe Microgranite which is a porphyritic granophyre lies on the margin between the granites and the volcanics of the Lobatse Group. The Ntlhantlhe Microgranite shows rapid transition into the felsites of the Kanye Volcanics which consists predominantly of homogeneous fine grained to aphanitic rocks with occasional feldspar phenocrysts (Womald & Downey, 1999).

Modipe gabbro occurs within the Gaborone igneous complex, and recent geochronological information indicates that it was emplaced contemporaneously with the Gaborone igneous complex (Denyszyn et al., 2013). This implies that the Modipe Gabbro is part of the Gaborone Igneous Complex. The Mmathethe Granite is part of the Neoarchaean granitic magmatism situated on the northern margin of the Kaapvaal craton in the south-eastern part of Botswana. Mapeo et al. (1998) did a geochronological study of the Mmathethe granite and obtained a minimum emplacement age of 2775 + 7.4 Ma from zircon analyses. This age demonstrated that the Mmathethe Granite is coeval with various granite phases of the Gaborone Granite as well as the surrounding volcanic rocks of the Lobatse Group (Sibiya, 1988).

The granites and volcanics are unconformably overlain by the Transvaal Supergroup and Waterberg sediments which can be mainly found towards the southwest of the complex. The Transvaal Supergroup contains a distinctive arenaceous rock unit at the base which is referred to as the Black Reef Quartzite Formation which overlies the Archaean rocks of the Lobatse Group. The Black Reef Quartzite forms a ridge-feature for most of its length. Overlying the Black Reef Quartzite Formation are carbonate rocks containing prominent chert horizons (Carney et al., 1994).

The Waterberg Group overlies the Transvaal Supergroup in South-east Botswana. It is made of arenaceous rocks in varying shades of pink, red and purple which are commonly referred to as red beds. In the northern areas of South-east Botswana (in the study area) the Waterberg Group units are overlain by late Palaeozoic sandstone, shale and coal deposits of the Karoo Supergroup (Carney et al., 1994). Dolerite intrusions in South-east Botswana are common and have intruded all the rock units including the Karoo sediments (Fig. 6). The area has been affected by extensive faulting as can be seen in the geologic map. Additionally, the recent Quaternary deposits of Pleistocene and Holocene are found along the active river system like Notwane, Madikwe and Limpopo. Those valleys are characterized by sand and silt deposits often overlying some

calcrete. The map below shows the upper geology of south east of Botswana between latitudes $24.0^0$S and $24.8^0$S and longitude $25.8^0$E and $26.9^0$E

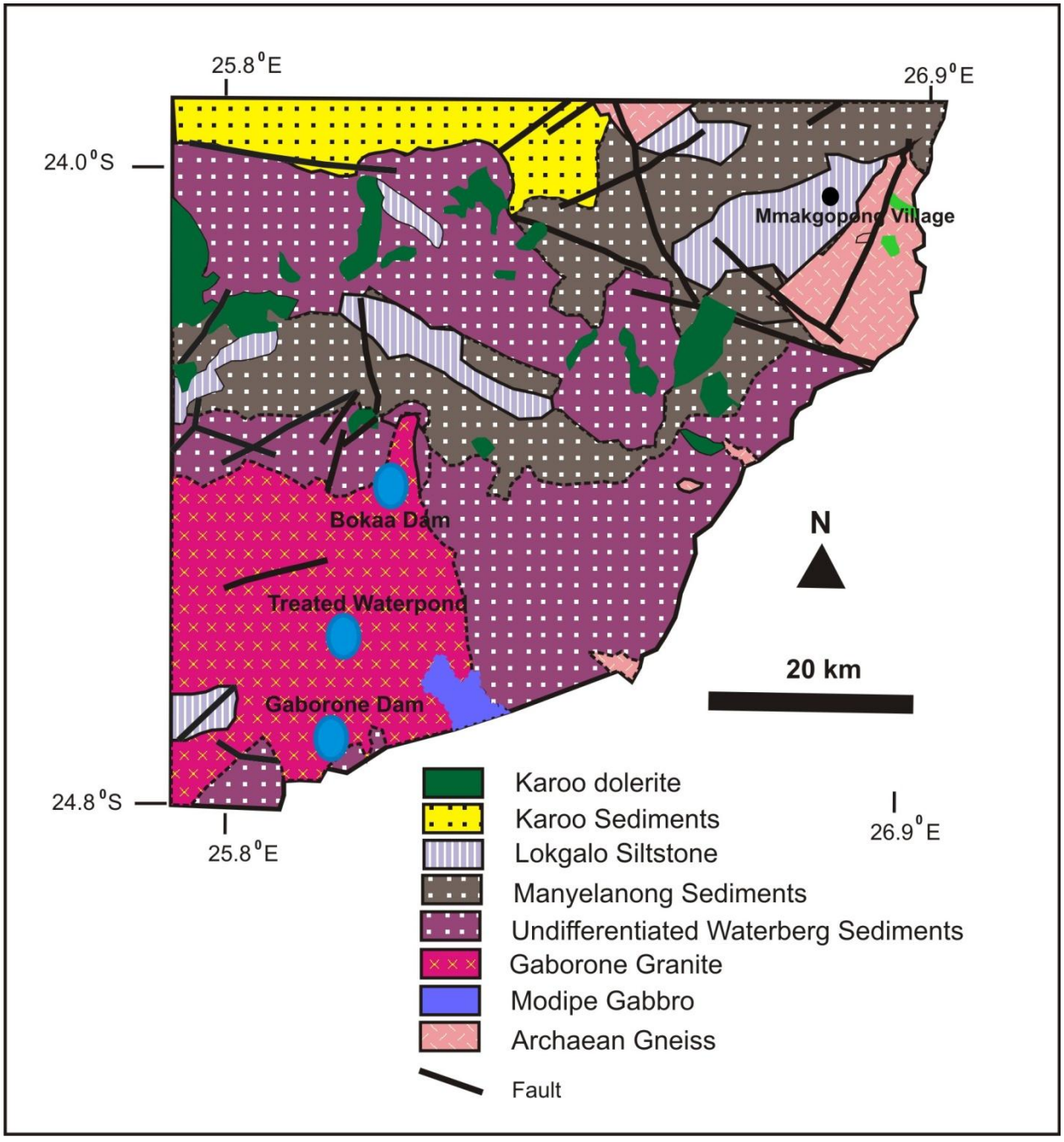


Figure 6: Geology of South Eastern Botswana.

### *1.4.5 Hydrogeology*

Notwane catchment is part of Limpopo basin that is characterized by 4 major geologic units: Achaean basement and gneisses, Proterozoic sedimentary units (i.e. Waterberg Group), the Karoo Supergroup and Karoo age dykes and intrusions. However, the study area upstream of Gaborone Dam (Ramotswa village) there is presence of dolomite which forms the karstic aquifer that supplied the community. Also the catchment has the most extensive geologic formation the Achaean basement and gneisses which underlay areas in Gaborone and the northeastern half of Botswana (Figure 6) has low groundwater potential. The Karoo Supergroup and Proterozoic sedimentary formations form fractured-porous and porous aquifers, they are found downstream of study area where there is Masama well field which has high yields in terms of groundwater and boost supply of water to Gaborone city. Furthermore there are fault lines downstream before the catchment outlet that cut across Notwane River and has potential of significant groundwater.

### *1.4.6 Soils*

The dominant soil type in the study area is ferric luvisols. However, according to Moganane (1989) the study area is characterised by various soil types. For instance in Kgatleng (middle of study area) the soils are reddish brown medium textured and slightly acidic to neutral derived from basic rock forms around the Modipe Gabbro hill in the area. In addition to that areas downstream between Mochudi and Oliphants Drift the soils are slightly neutral and composed of sand soils from Kalahari deposits as well as from the Waterberg and sandstones. Also found in the area are alluvial soils which are confided along Notwane River and its tributaries (Metsimotlhaba, Thagale and Monametsana).

### *1.4.7 Land use*

Notwane catchment downstream of Gaborone dam is occupied with the city of Gaborone, Oodi, Morwa, Malotwane, Mmakgopong villages and other small settlements. There are several economic activities in and around the city leading to major and small-scale industrial, commercial and institutional developments, the catchment has witnessed changes in land use due to growth in individual homesteads and hence settlement is the dominant land use followed by agriculture where farmers utilise surface water from Notwane River for irrigation and livestock. The land is also occupied with ploughing fields far from Notwane River whereby farmers plough

once a year during rainy seasons. There are small-scale farming practices including poultry to support the urban population.

### *1.4.8 Vegetation*

The South East of Botswana has vegetation comprising of five species of vegetation, sandveld tree and shrub savanna, hardveld woodland and tree savanna, hills and rocky outcrops woodland, depressions thicket and shrub savanna, and lastly the riverine woodland (Moganane, 1989). Most parts of the study area comprises of acacia erubescens tree savanna vegetation structure which is found along Notwane River from Gaborone to Mochudi village. Areas around Mochudi village on the western side are covered with croton gratismus woodland which has species such as combretum molle ximenia Americana.

# 2.0 LITERATURE REVIEW

Tanimu et al. (2013) carried out a study on the effects of sewage pollution on water quality of Samaru Stream, Zaria in Nigeria. The findings revealed that the downstream stations had a better water quality than the upstream, where the source of pollution was located. In the upstream side the water was affected by bacteria and algae. According to (Tanimu et al., 2013) an ultra-filtration of the polluted water was done by aquatic macrophytes as water flows from upstream to downstream. Furthermore, the researcher concluded that major-ion chemistry can be used as a general indicator of water quality because the analyses of these ions help to identify some of the physical-chemical processes that affect the composition of natural waters.

A review was done by Yang et al. (2012) in characterizing interactions between surface water and groundwater in the Jialu River basin using major ion chemistry and stable isotopes in China. The result revealed that concentration of $Cl^-$ ion significantly increased in river water due to discharge of a large amount of untreated or slightly treated waste water. The result also revealed that nitrate and potassium show maximum concentrations in groundwater.

Bhattacharya (2010) carried out a study on artificial groundwater recharge with a special reference to India. It was observed that due to over-exploitation of groundwater, there was decline in groundwater levels resulting in shortage of supply of water, and intrusion of saline water in coastal areas. This lead to the need for artificial recharge of groundwater by augmenting the natural infiltration of precipitation or surface-water into underground formation. The research concluded that the cost of a recharge scheme in general, depends upon the degree of treatment of the source-water, the distance over which the source-water needs to be transported, the stability of the recharge structure and resistance to silting or clogging.

A relevant study on artificial recharge via boreholes using treated wastewater possibilities and prospects was done by Voudouris (2011) in Cyprus and it was concluded that artificial recharge is an internationally acceptable practice, also as the other options available for increasing the groundwater reserves in the South-Eastern Mesaoria aquifer. Borehole recharge could be a solution for regions with low water availability and deteriorating water quality due to saline water intrusion. However, it was noted that treated water use require the public to overcome the psychological barrier and that could be achieved through special educational programs for stakeholders.

A related study was conducted by Radell & Katz (1991) whereby water sampled from 189 wells tapping the Biscayne aquifer, southeast Florida (United States of America) was predominantly a calcium bicarbonate type with some mixed types occurring in coastal areas and near major canals. According to nonparametric statistical tests of major ions and dissolved solids, the concentrations of calcium, sodium, bicarbonate and dissolved solids increased significantly with well depth (0.05 significance level), probably a result of less circulation at depth. Potassium and nitrate concentrations decreased significantly with depth. Although the source of recharge to the aquifer varies seasonally, there was no statistical difference in the concentration of major ions in paired water samples from 27 shallow wells collected during wet and dry seasons (Radell & Katz, 1991).

A similar study on the assessment of quality of groundwater in relation to heavy metal pollution and its implication on human health in Sialkot was carried out by Ullah et al. (2009). The groundwater quality of Sialkot, an industrial city of Pakistan was evaluated using water samples collected from 25 localities during October-November 2005. Twenty-two physiochemical parameters including pH, Electric Conductivity (EC), Total Dissolved Solids (TDS), Salinity, Temperature, Turbidity, Sulphate (SO4) Chloride (Cl), Total Hardness, Iodide, Fluoride, Ferric (Fe+3), Nitrate (NO3), Manganese (Mn), Total Chlorine, Alkalinity, Zinc (Zn), Lead (Pb), Iron (Fe), Copper (Cu), Nickel (Ni) and Chromium (Cr). The results were compared with standard guidelines of World Health Organization (WHO, 1996) and Pakistan Standard Quality Control Authority (PSQCA, 1996) for groundwater quality. The results revealed that the groundwater of the study area cannot be considered of good quality as it was highly turbid (57% of total sites) with high level of Zn, Fe and Pb, which were above WHO and PSQCA permissible limits. The spatial distribution maps of water quality parameters were also produced using Geographic Information System (GIS).

Tiwari (2011) carried a study in assessment of quality and pollution potential of Jawa Block Rewa District, Madhya Pradesh in India. Thirty groundwater samples were collected in one litre clean polythene bottles during November 2010 to cover the entire area and analysed for various chemical parameters following standard method. The electrical conductivity (EC), total dissolved solids (TDS) and total hardness (TH) were measured in the field whereas calcium, magnesium, sodium, potassium, chloride, bicarbonate, sulphate, fluoride and nitrate were determined in the laboratory. Accordingly, the hydrochemical analysis of the study revealed that the groundwater

in the study area was moderately hard to very hard and alkaline in nature. The study also revealed that Ca-Mg-HCO3 and Ca-Mg-Cl-SO4 were the two main facies present in the area. According to this study, the higher values of electrical conductance in shale aquifer may have been due to enough time for reaction between groundwater and impervious shale whereas comparatively lesser amount of EC in sandstone aquifer was due to its hydrogeological characteristics. In this study the hydrochemical analyses revealed that all the measured values of TDS exceeded the desirable limit set World Health Organisation (1984) and Indian Standard Institute (1991) and the concentration of sulphate was also high. According to the author, this high concentration of sulphate associated with shale aquifer was due to the presence of gypsum ($CaSO_4.2H_2$) and barite (BaSO4) nodules in the shale.

Anabella et al. (2014) carried out a study on the assessment, monitoring and protection of groundwater pollution in urban areas Cordoba city, Argentina. In this study, the analyzed water samples showed that urban storm waters consisted of very high concentrations of TSS, BOD, COD, N-NH4+, N-NO3-, and PO4. High concentration of sulphate and chlorine were also found in the groundwater. In some industrial areas, concentrations of nitrates, arsenic, fluorine and bacteria (Coliformes) exceed tolerable limits. The study concluded that the major sources of pollutant were urban wastewater, urban storm water and solid waste disposal sites.

A study was conducted by Halder & Islam (2015) to find out the pollution situation of Turag River in Bangladesh. Surface water samples of the rivers were collected from four different points of the river in two seasons during the period of April 2013 to July 2013 which covered dry and wet periods. The result revealed that the water quality of Turag river may not be in a position to sustain the aquatic life and not suitable for using domestic purpose. This was indicated by the very low dissolved oxygen levels and other measured parameters in the river water. The maximum recorded values of pH, colour, turbidity, biochemical oxygen demand (BOD5), hardness, total dissolved solids (TDS), chloride ($Cl^-$), carbon-di-oxide ($CO_2$) and chemical oxygen demand (COD) were 7.1, 625 ptcu, 97.2, 4.65 mg/L, 1816 mg/L, 676mg/L, 5 mg/L, 15.5, and 78 mg/L, respectively. The maximum concentration of turbidity, BOD, hardness, TDS and COD found in the Turag River was much higher than the standard permissible limit.

Dhakyanaika & Kumara (2010) conducted a similar study on effects of pollution in Krishni River on the quality of groundwater, which is abstracted through shallow and deep hand pumps

placed in the close vicinity of River Krishni in India. Sampling was done at water supply, waste water drains coming from different industries and discharging into the river and areas relatively unpolluted stretch of the river. The result of their investigation revealed that the groundwater abstracted from shallow as well as deep aquifer was polluted. The groundwater was found to be polluted in terms of color, organic compounds and by the presence of coliform bacteria caused by the effluents from industries.

A study in hydrochemical analysis and evaluation of groundwater quality in Tumkur Taluk, Karnataka State, India was reviewed by Sadashivaiahet al. (2008). The study area was a semi-arid region and frequently facing water scarcity as well as quality problem. The major activities were agriculture, horticulture and animal husbandry. Water samples were collected from 269 stations during pre-monsoon and 279 locations during post-monsoon of the year 2006, and were subjected to analysis for chemical characteristics. It was found that about 98% of the samples were good and they fell in the suitable range for irrigation purpose.

A relevant study conducted by Singhet al. (2004) found out that the irrigation use of treated effluent in a long run cause reduction of yield and plant root diseases due to accumulation of metals in India.

Another study was carried out by Shanti & Meenabal (2012) on the physicochemical analysis of groundwater near municipal solid waste dumping sites in Coimbatore city in India. Ten groundwater samples were collected during the rainy season in 2011 from the study area and the samples were analysed for various physical and chemical properties. They revealed that the total dissolved solids varied from 565 mg/l to 912 mg/l also other parameters such pH, Total Suspended Solid, Total Solids, Total Alkalinity, Chemical Oxygen Demand, Nitrate, Cl-, and F- were found to be within permissible limits that do not cause pollution.

Das & Das (2003) carried a study on the impacts of waste water discharge on the soil and groundwater at Mysore, Karnataka (India). Groundwater samples and effluent samples were collected and analysed for pH, nitrates, BOD, sulphate, phosphate, and COD. They concluded that discharge of wastewater effectively reduces contaminants due to adsorption in soil composition and hence preventing groundwater sources from pollution.

A review was done by Hashemi et al. (2013) on the natural versus artificial groundwater recharge quantification through inverse modelling in Iran. The study used the MODFLOW-2000 to estimate recharge for both steady and unsteady-state conditions. The model was calibrated and verified based on the observed hydraulic head in observation wells, model precision, uncertainty and model sensitivity were analysed in all modelling steps. It was found out that the ephemeral river contributes only 20% of aquifer recharge and 80% from floodwater; therefore there was need to increase recharge volume of the aquifer by artificial recharge since recharge through the river channel increased much only during major flood events.

A study was carried out by Beyerle et al. (1999) on infiltration of river water to a shallow aquifer using $^{3}H/^{3}He$, noble gases and CFCs in Switzerland. It was highlighted $^{3}H/^{3}He$ dating method provides valuable information on the recharge dynamics. However, it was found out that the age of groundwater in boreholes close to the river was young during times of active river discharge, also the noble gas temperature in boreholes close to the river varied seasonally and the temperature in all the samples lies close to the mean annual temperature of the river water. However with those findings, it was concluded that the water in boreholes close to the river can be interpreted in terms of mixing of recently infiltrated river water with older groundwater.

Wu et al. (2012) used an internet survey to gauge the attitude and intentions of Salisbury residents on the use of storm water treated. The survey results suggested that the community had a positive attitude toward using the treated storm water for non-potable uses, and they consider that using the storm water treated through the managed aquifer recharge process was not being likely to lead to health risks, in particular for uses that do not have close human contact.

Schroeder (1995) carried out a study on potential for chemical transport beneath a storm-runoff recharge (retention) basin at an industrial catchment in Fresno, California. 20 inorganic elements and about the same number of organic compounds, primarily chlorine pesticides and polycyclic aromatic hydrocarbons were collected beneath recharge basin. It was revealed that wide variety of chemicals from urban runoff were found at elevated concentrations in sediment that accumulated in a storm-runoff recharge basin in an industrial part of the city of Fresno. Although it was found out that there was leaching of contaminants associated with sediments from the recharge basin, there was a decrease in concentrations with increasing sediment depth, and the

extremely low level of contaminants in two monitor wells adjacent to the basin, confirmed the absence of contaminant transport to the water table.

Thomsen et al. (2004) researched on the hydrogeological mapping for site-specific groundwater protection zones in Denmark. The paper highlighted that the Danish farmers have highly developed agriculture with intensive use of fertilizers, manure and pesticides. Two-thirds of the Danish land area is managed by farms with a high pig meat production totalling 25 million pigs per year. Pollution from farming is a challenge to water supply in Denmark. It was also reviewed that many shallow aquifers suffer from groundwater pollution, especially from nitrate and pesticides. In recent decades many water works have been closed, forced to drill deeper, or forced to buy their water from neighbouring water supplies. Pesticide pollution, especially in suburban areas, has led to closure of several major well fields. Leaching from waste disposal sites and other point sources has closed several water supply wells. It was also found out that some water works suffered from nickel pollution, mainly due to over-exploitation of aquifer however. In this study it was concluded that the maps are used to establish site specific groundwater protection zones and associated regulation of land use to prevent groundwater pollution. The fundamental concept of site-specific groundwater protection zones is that some areas are more vulnerable to groundwater pollution than others. The goal is thus subdivision of a given area according to the different potential of the various sub-areas for specific purposes and uses.

A study was done by Foster & Chilton (2003) on "downstream of downtown: urban wastewater as groundwater recharge" using five locations with sewage water treatment plant Lima suburb (Peru), Wadi Dhuleilb(Jordan), Mezquital Valley(Mexico), Leon (Gto)(Mexico) and Hat Yai (Thailand). At all the location it was found out that there was groundwater recharge from the secondary treated wastewater. At Lima and Mezquital Valley the vadose zone chlorine balance suggests field infiltration rates of 1,400–1,600 mm/year with over 60% of the wastewater delivery. It was also found out that at Leon, aquifer groundwater levels have stabilised locally as a result of wastewater reuse and incidental recharge, despite heavy abstraction for municipal water supply.

Al-Shaibani (2008) conducted a study on hydrogeology and hydrochemistry of a shallow alluvial aquifer, western Saudi Arabia. The hydrochemistry was done upstream and down-gradient from

potential contamination sources in Jeddah City in dry and wet seasons prior to and after the installation of major drainage and wastewater facilities. The results found indicated that both groundwater and runoff showed similar chemical signature, which is mostly of chloride-sulphate-bicarbonate and sodium-calcium type. Groundwater downstream of the city, though of poorer quality than upstream, showed significant improvement after the installation of a concrete runoff tunnel and a wastewater treatment plant. Concentrations of many of the groundwater quality indicators such as TDS, coliform bacteria, and nitrate were found exceeding US Environmental Protection Agency drinking-water standards. Heavy metal content was within allowable limits by local and international standards. The author also concluded that chemical analysis also suggest strong influence of groundwater quality is associated with stream runoff and sewage water.

Dano et al. (2008) conducted a study on the fate of individual sewage disposal system, waste water disposal within regolith in mountainous terrain at Creek Basin (USA). The individual sewage disposal system (ISDS) was traced through geophysical, hydrologic and geochemical methods. It was found out that the effluent discharged to regolith was overlying fractured rocks and flow laterally in the regolith way from the infiltration area. Also in unusual high recharge years it was found that the effluent seeps into the bedrock quickly. Even though the ISDS effluent was percolating through unsaturated region, it was concluded that it perched on the bedrock surface and traversed to unsaturated zones in the fractured aquifer before joining the regional groundwater system and that flow path does not reduce solute concentration in the effluent. Furthermore it was also found out there was a chemical similarity in both the effluent and anthropogenic component affecting both surface water and groundwater.

Reichard & Brown (2009) conducted a study on detecting groundwater contamination of a river in Georgia, USA using base-flow sampling. During the initial 12 month phase of this investigation on the Canoochee River, weekly samples were collected using a coarse spatial scale in order to detect major nutrient inputs. It was found that the pH and electrical conductivity changes linked to the subsurface discharge of municipal and industrial effluent from land application system (LAS) spray fields, also the data showed that the principal source of excessive nitrogen was a LAS associated with a poultry processing facility. Moreover, temporal variations in the data indicated that contaminated groundwater was having a more significant

impact on the water quality of the Canoochee River than surface-water inputs. Additional samples collected from springs and boreholes along the riverbank verified the presence of two contaminant plumes. One plume was found to contain high concentrations of nitrate, ammonia and phosphate and is clearly associated with an unlined waste water lagoon that lies adjacent to the river. The second plume was characterized by having elevated concentrations of only nitrate, which indicated that it originated from beneath the LAS spray fields.

Another relevant study was done in Nuthegraben Lowland catchment (south of Berlin) on Pharmaceuticals as indictors of sewage-influenced groundwater by Müller et al. (2012). Groundwater and surface water samples were collected and analysed for the pharmaceutical substances clofibric acid, bezafibrate, diclofenac, carbamazepine and primidone, the main ions and organic carbon. The pharmaceutical substances were detected at concentrations up to microgram per litre level in groundwater and surface-water samples from the Nuthegraben Lowland area and from the former irrigation farms concentrations detected in groundwater are generally much lower than in surface water and there is significant variation in the distribution of pharmaceutical concentrations in groundwater. Groundwater influenced by the irrigation of sewage water shows higher primidone and clofibric. Groundwater influenced by recent discharge of treated sewage water into the surface water shows high carbamazepine concentrations while concentrations of primidone and clofibric acid are low.

Hoque et al. (2014) researched on tracing recharge to aquifers beneath an Asian megacity with Cl/Br and stable isotopes in Dhaka (Bangladesh).It was found out that values of Cl/Br > 500 were common in groundwater beneath western Dhaka in areas less than 3 km from the river, and in rivers and sewers around and within the city. The study showed that groundwater beneath western Dhaka is strongly influenced by infiltration of effluent from leaking sewers and unsewered sanitation, and by river-bank infiltration from the Turag- Buriganga river system which bounds the western limit of the city. The results of Cl/Br and Cl concentrations also revealed that 23% of wells sampled in Dhaka were influenced by saline connate water in amounts up to 1%.

A relevant study was done by Yuce et al. (2006) in Turkey on soil and water pollution derived from anthropogenic activities in the Porsuk River Basin. Surface and groundwater samples were collected from various locations in the study area between May and October in 2001. The results

obtained revealed that some trace elements, (Pb, Cr, Mn, Fe, and Cd) were present in high concentrations both in the surface and groundwater besides to the extremely high quantities of phosphorus, nitrogen and sulphide compounds. High concentration of Cd, N and S are found in the groundwater. In addition, analysis of samples also indicated that there are no considerable contaminations in terms of local pesticides. Furthermore it was concluded that groundwater was not suitable for drinking according to Turkish standards, European Union Standards (EU) and World Health Organization (WHO).

In a study done by Shomar (2011) on groundwater contaminations and health perspectives in developing world at Gaza Strip, the results of a 10-year monitoring program revealed that more than 90% of the available water was not suitable for drinking purposes as a result of elevated chemical contaminants as well as microbiological organisms. The researcher concluded that much of the groundwater deterioration was directly traceable to overpopulation and failure of the existing infrastructure to cope.

Reddy et al. (2012) conducted a study on surface water of Hussainsagar Lake in India. It was found out that the surface water was contaminated with heavy metals including potential toxic elements (PTEs) of high, moderate and low toxic nature. According to the author the lake was receiving large quantities of untreated municipal sewage containing industrial effluents. It was also concluded that most of contaminants in surface water exceeded the maximum permissible limits of national (ICMR) standards for drinking water.

# 3.0 METHODOLOGY

## 3.1 General

In order to achieve the mentioned objective of the research primary and secondary data were collected at different times of the research period. Primary data were collected both in the field and in the laboratory using different techniques. Secondary data such as location of boreholes, geological reports and maps, rainfall records, soils and land use were collected from different office in Gaborone.

Surface water and groundwater samples were collected from February to April in 2016 from different parts of the study area (Figures 8 & 9). Physico-chemical parameters such as pH, total dissolved solids (TDS), electrical conductivity (EC) and temperature were measured for all the samples using portable digital multi parameter analyser in situ immediately after sampling. All the samples were analysed for major cations, anions trace elements.

## 3.2 Data Collection

Forty-one surface water samples were collected starting from the Gaborone dam downstream along the river to the catchment common outlet at Mmakgopong village: twenty six surface water samples were collected at different location from Notwane River starting from the upstream side of the study area (after the Gaborone dam) to the outlet (Figure 8 & 9), nine surface water samples were also collected from the tributaries of the Notwane River before their respective junction point and six samples were collected from dams and small ponds inside the study area. Surface water sampling was done following the flow direction of the surface waters. One sample was collected from the pond that is located at mouth of the last treatment plant (Fig. 11) as a representative to the treated wastewater. Fifteen groundwater samples were collected from the boreholes that are found in the area close to the Notwane River and far away from the influence of the river (Figure 9).

The water samples were collected in one litre Polyethylene terephthalate bottles (Fig. 7). Prior to sampling the bottles were rinsed with samples to be collected. All the sampling points were located with the help of GPS.

Figure 7. Sampling instruments

### 3.3 Data Analysis

The water samples were analysed for major cations ($Ca^{2+}$, $Mg^{2+}$, $K^{+}$, $Na^{+}$ and $Li^{+}$), anions ($HCO_3^{-}$, $Cl^{-}$, $SO_4^{2-}$, $NO_3^{-}$, $F^{-}$, $PO_4^{3-}$ and $CO_3^{2-}$ ) and trace elements. The trace elements that were analysed were arsenic (As), barium (Ba), cadmium (Cd), Cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), manganese (Mn), lead (Pb), nickel (Ni) and zinc (Zn). All the samples were filtered using 45µm membrane before analyses (Fig. 12).

The major cations and all the trace elements were analysed in the geochemistry laboratory of the Department of Geology, University of Botswana using Inductively Coupled Plasma Mass Spectrometry or ICP-MS. The anions were analysed in the water quality laboratory of the Department of Water Affairs. For all the water samples alkalinity and hardness were determined using AquaChem software.

The analytical precisions for the measurements of ions were determined by calculating the ionic balance error using the following formula.

$$\text{Where, E.N (\%)} = \left[\frac{(\text{Sum cations} - \text{Sum anions})}{(\text{Sum cations} + \text{Sum anions})}\right] * 100$$

All the measurements are in milli equivalents per litre. It is found that the majority of the analyses were within the acceptable range.

Simple descriptive statistical method was utilized for the analyses of the water chemistry data. AquaChem and Suffer software's were also used for analyses the water chemistry data. AquaChem software is a fully integrated statistical package developed specifically for graphical and numerical analyses of aqueous geochemical data sets. Piper diagram and radial plots were prepared using this software for graphical presentation of the results and compare water quality data in the area. Suffer software was used to show contour map of distribution of elements in groundwater by Kriging method. Gibb's diagram was also used to see the relationship of water composition and aquifer lithological characteristics.

The suitability of the waters of the studied area for drinking purpose was evaluated with respect to the standard set by both the World Health Organisation (WHO, 2004) and the Botswana Bureau of Standard (BOBS second edition, 2009).

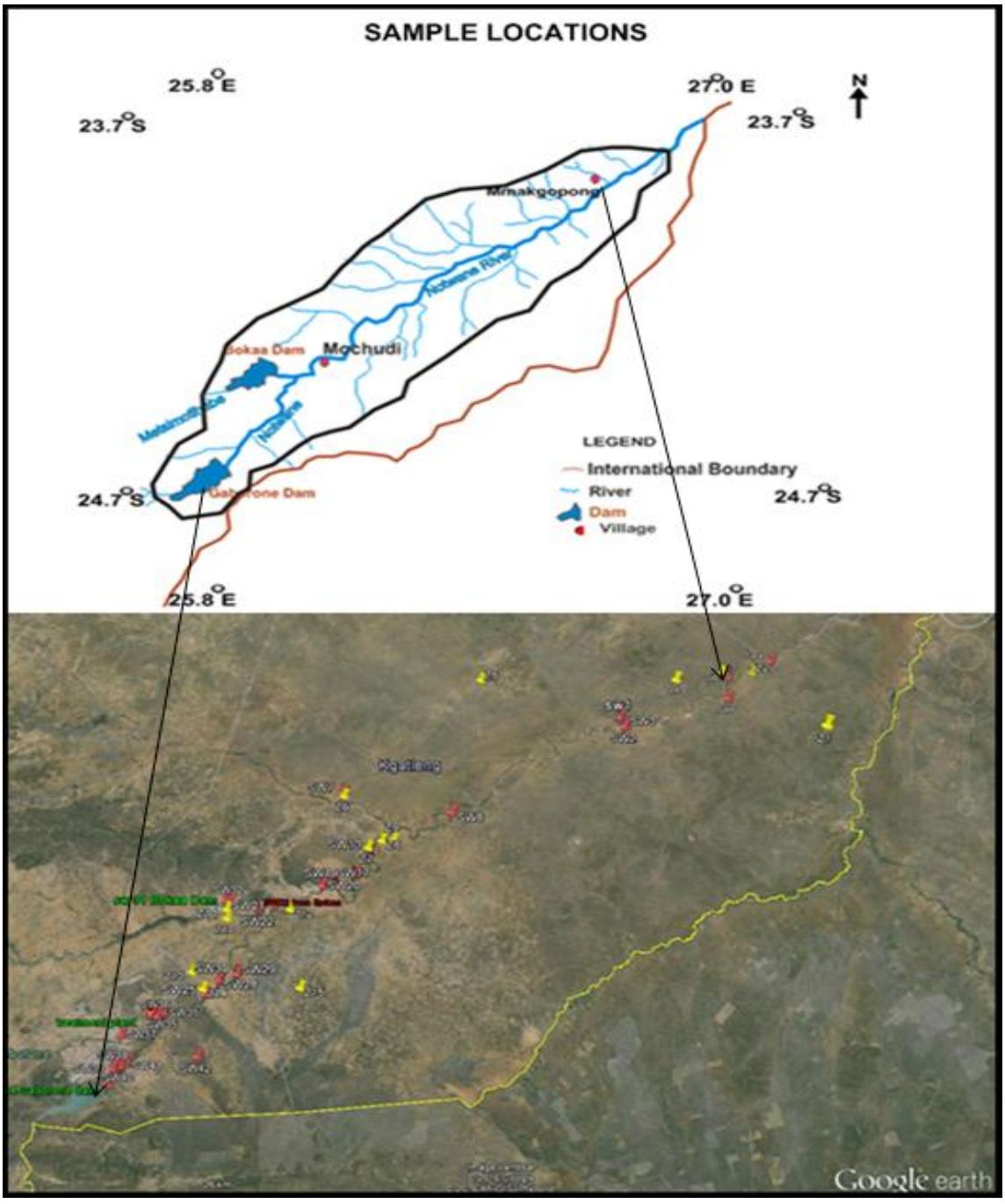


Figure 8. Sample location (red points are surface water sample location and yellow points are groundwater sampling locations).

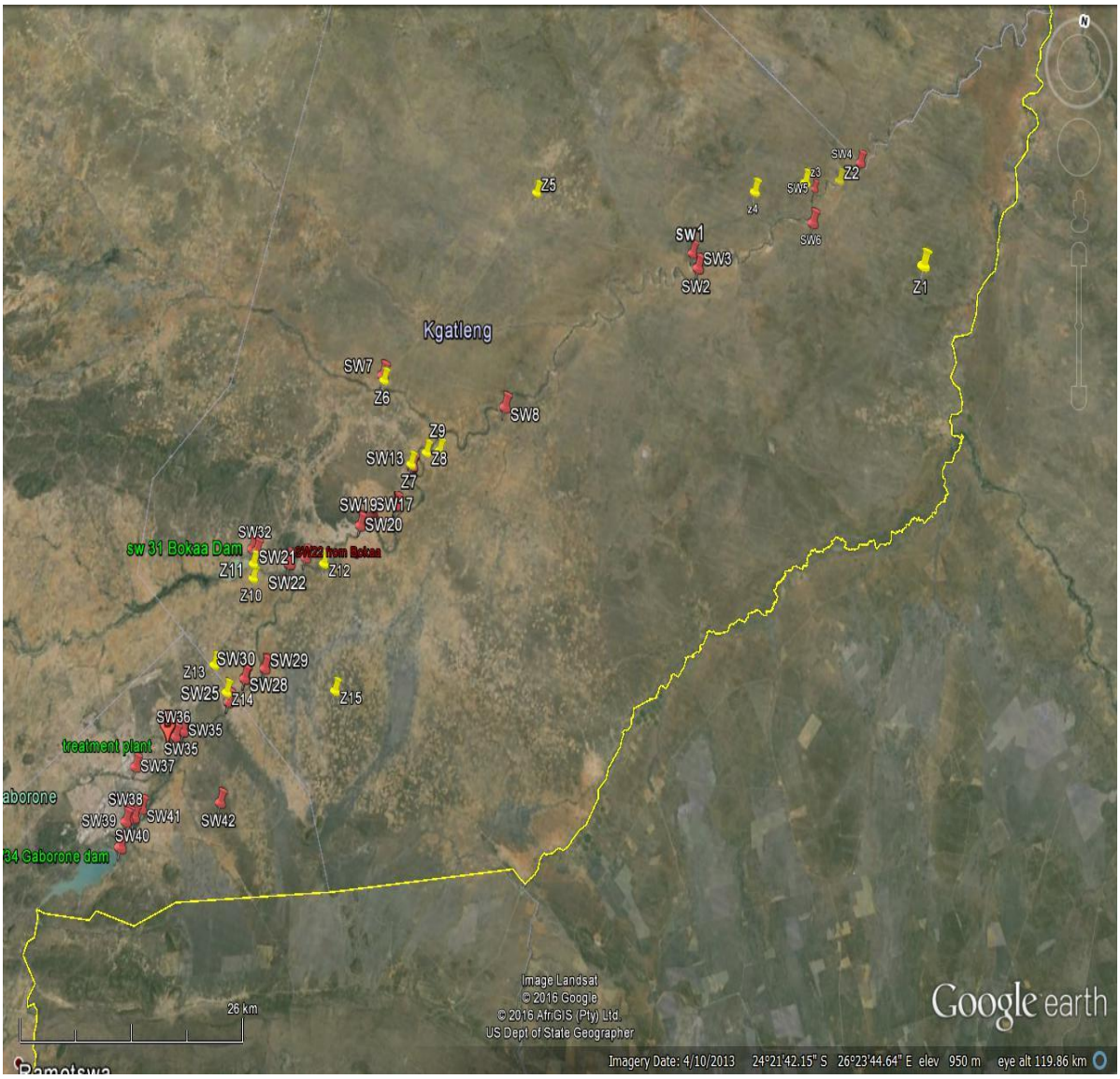


Figure 9. Sampling points with their corresponding sampling code.

Figure 10 and 11 below show the surface water in Notwane River during sampling and the treated wastewater pond. After sampling both waters the samples were filtered into smaller bottles (Figure 12).

Figure 10. Sampling surface water in Notwane River at Mmakgopong village.

Figure 11. Treated wastewater pond

Figure 12. Surface water and groundwater samples after filtering.

# 4.0 RESULTS

## 4.1 Physico-Chemical Parameters

### *4.1.1 Temperature*

The temperatures measured for the surface water, treated wastewater and at the source of the groundwater are given in the tables 2 to 4 below. The temperature of the surface water ranges from 24.7 to 36.3 $^0$C with a mean value of 29.91 $^0$C. 57% of the total measured surface water samples have a temperature greater than 29$^0$C whereas 43% have a temperature of 29$^0$C and below. The temperature of the treated water is 28 $^0$C. The temperature of the groundwater ranges from 24.3 $^0$C to 33.6 $^0$C with a mean value of 30.17 $^0$C. 73% of the total groundwater samples have a temperature greater than 29$^0$ C whereas 27 % are 29$^0$ C and below.

### *4.1.2 pH*

Surface water pH ranges from 7.47 to 9.93 with a mean value of 8.56. The minimum value was recorded in sample SW24 measured in small stream, which is a tributary to Notwane River, before a junction point and the maximum was recorded in the sample SW21 measured in a stream which is a tributary of Notwane River, before it junction at Bokaa village. Out of the forty one samples 70 % of the total samples have a pH of 8.00 and above whereas the remaining has a pH less than 8.00. In overall the surface water is slightly alkaline to alkaline.

The pH of treated wastewater is 7.65 which slightly alkaline. Measured pH in the groundwater ranges from 6.82 to 9.44 with a mean value of 7.99. About 80% of the total samples of the groundwater have a pH of 7.44 and above whereas the remaining 20% have a pH less than 7.00. In general the pH of groundwater is slightly alkaline to alkaline. The pH less than 7.00 was recorded in the sample Z8, Z10 and Z15, which are located in Kgatleng district in the middle of the study area and Z8 is located in the river bank of Notwane River in the same district.

With the exception of the three samples in the groundwater, both groundwater and surface water of the study area show a high pH value as compared to the treated wastewater.

The figures below (Fig 13 & 14) show the pH distribution of surface water and groundwater samples excluding the treated waste water.

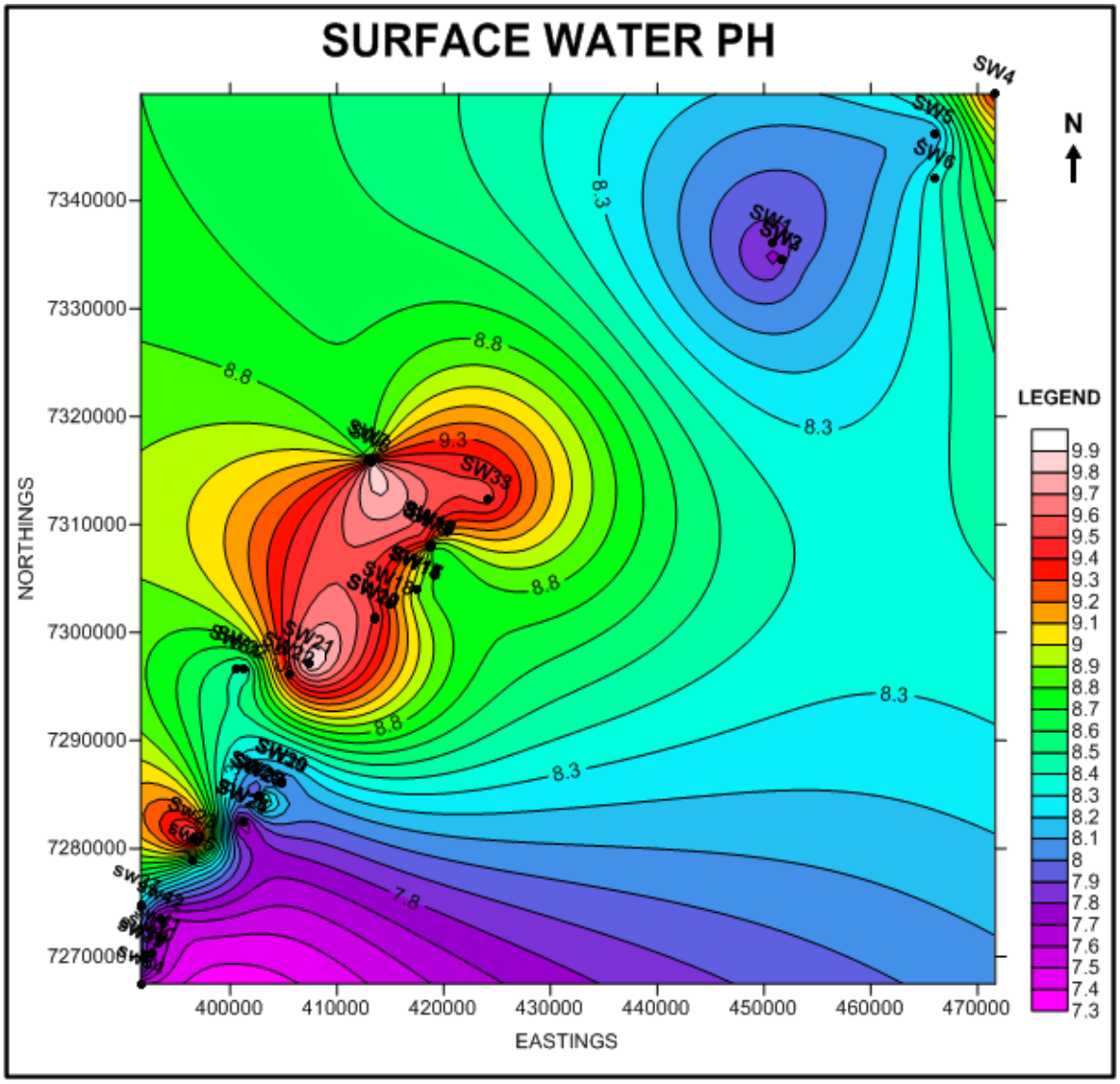


Figure 13. Surface water pH.

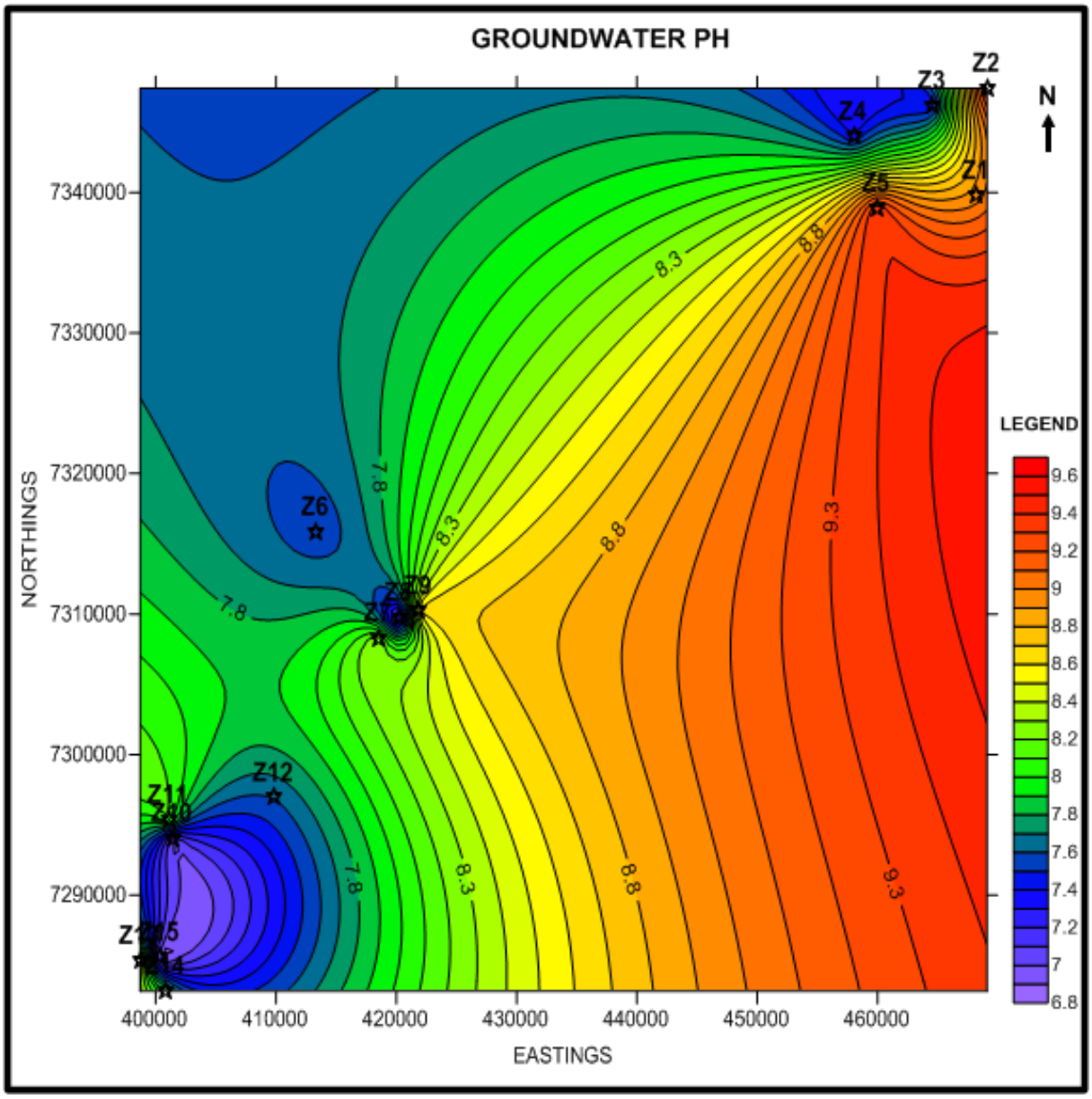


Figure 14. Groundwater pH.

### *4.1.3 Electrical Conductivity (EC) and Total Dissolved Solids (TDS)*

The measured EC of surface water ranges from 61.1µS/cm to 757 µS/cm with a mean value of 391.8µS/cm. Treated wastewater has an EC of 785µS/cm while the groundwater EC ranges from 160 to 14390 µS/cm with a mean value of 3856.87 µS/cm.

The measured TDS of the surface water is ranging from 47.3 to 538 ppm with a mean value of 279.40 ppm while treated wastewater has a TDS of 557 ppm. TDS values in the groundwater ranges from 114 to 10070 ppm with a mean value of 2750.51 ppm, which indicate that the average groundwater TDS is brackish based on the classification table below.

Table 1. Groundwater classification based on TDS (Freeze & Cherry, 1979).

| Category Total dissolved solids (mg/L) | |
|---|---|
| Fresh water | 0-1000 |
| Brackish water | 1000-10 000 |
| Saline water | 10 000-100 000 |
| Brine water | More than 100 000 |

In overall the highest value of both EC and TDS were measured in the groundwater of the catchment. 66.7% and 60% of the total groundwater samples have an EC of greater than 1000 µS/cm and a TDS greater than 1000 ppm, respectively.

The Figure below shows both TDS and EC of the surface water measured starting from the outlet downstream side of the river (SW1) to the upstream (SW30).The general trend shows that both TDS and EC increases from downstream to the upstream of study area.

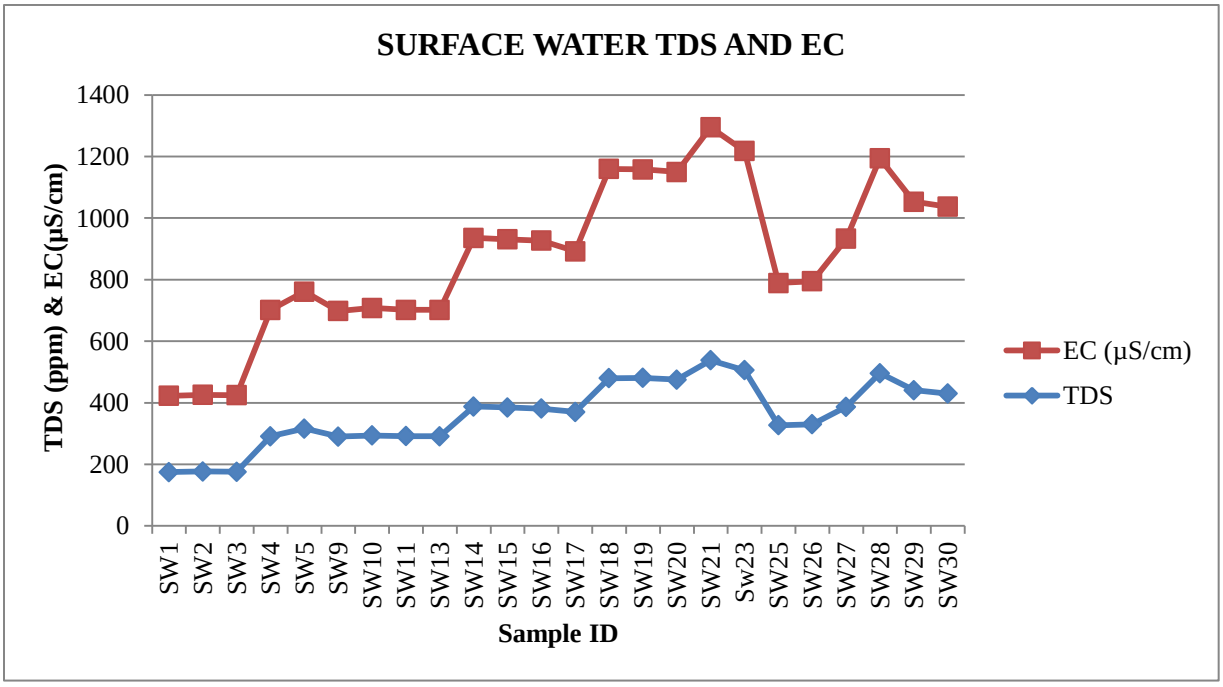


Figure 15. Notwane River TDS and EC.

Figures (16 & 17) below show the total dissolved solids concentrations in surface water and groundwater, excluding treated wastewater sample.

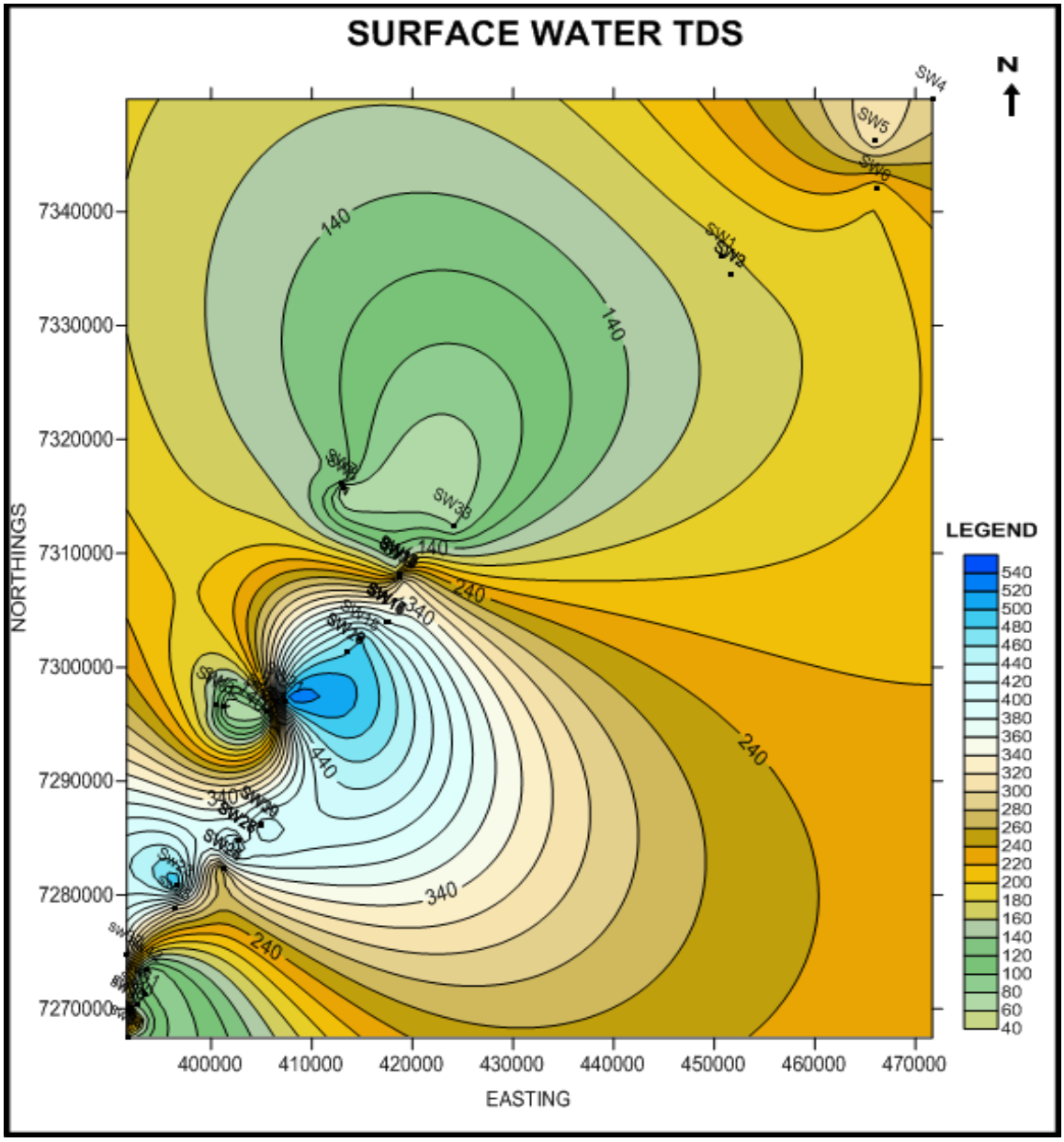


Figure 16. Surface water TDS.

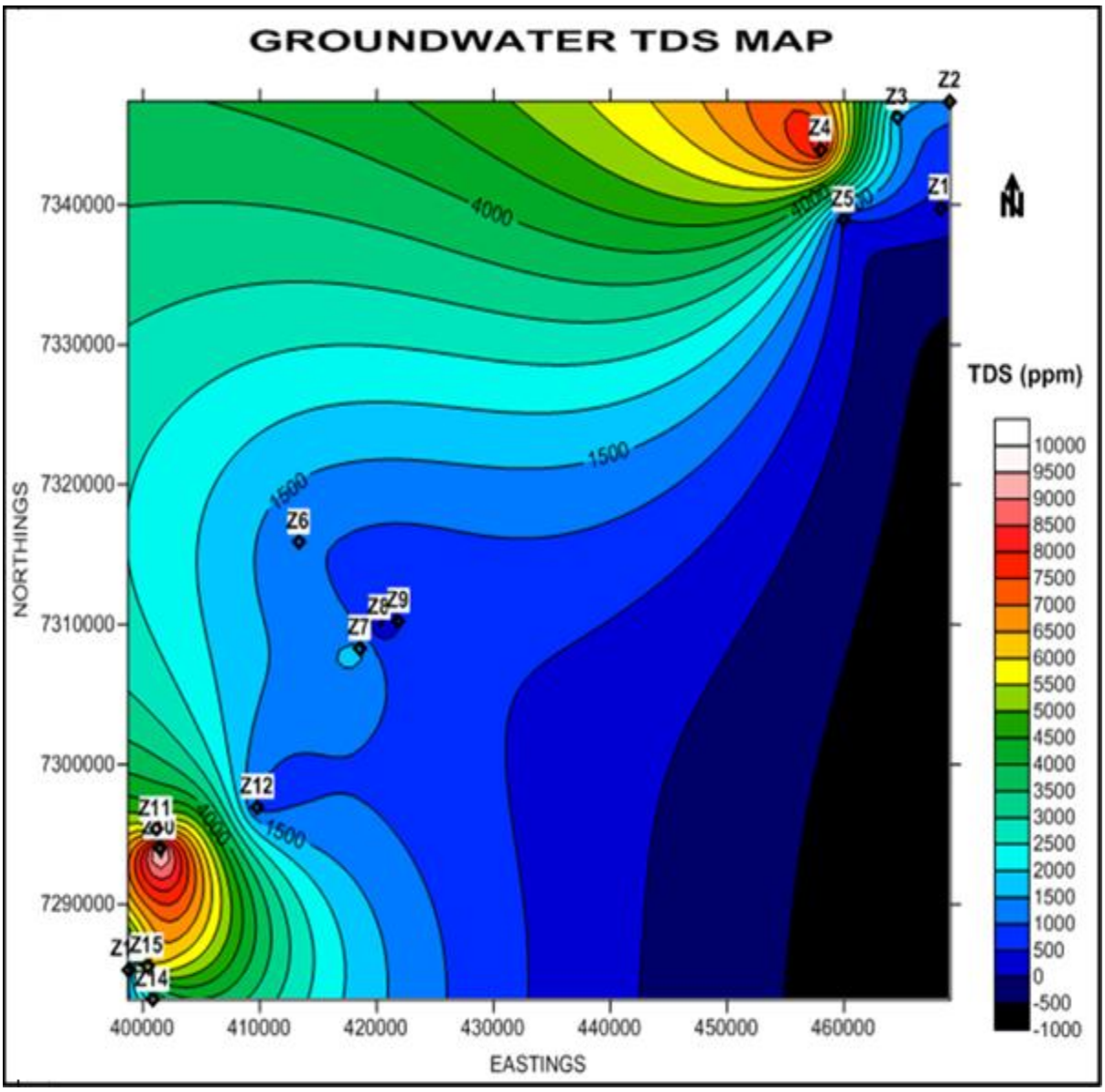


Figure 17. Groundwater TDS.

The Tables below show the parameters of surface water, treated wastewater and groundwater measured in situ during sampling.

Table 2. Surface water in situ parameters.

| Sample ID | EASTINGS | NORTHINGS | pH | TDS (ppm) | EC (µS/cm) | TEMPERATURE (ºC) |
|---|---|---|---|---|---|---|
| SW1 | 0450760 | 7336051 | 7.84 | 175 | 248 | 27.6 |
| SW2 | 0451664 | 7334476 | 7.72 | 177 | 249 | 28.6 |
| SW3 | 0451687 | 7334468 | 7.94 | 176 | 249 | 28.8 |
| SW4 | 0471669 | 7349856 | 9.41 | 291 | 411 | 33.3 |
| SW5 | 0465930 | 7346191 | 8.08 | 316 | 445 | 29.5 |
| SW6 | 0466082 | 7342005 | 8.37 | 203 | 286 | 29.8 |
| SW7 | 0413039 | 7316162 | 8.73 | 141 | 119.0 | 29.7 |
| SW8 | 0413189 | 7315746 | 9.89 | 47.3 | 66.8 | 29 |
| SW9 | 0418726 | 7308038 | 8.86 | 290 | 408 | 31.9 |
| SW10 | 0418710 | 7307986 | 8.95 | 294 | 414 | 32.2 |
| SW11 | 0418741 | 7307930 | 8.86 | 292 | 410 | 32.1 |
| SW12 POND NEAR RIVER | 0418771 | 7308135 | 9.53 | 117 | 165.2 | 36.3 |
| SW13 | 0418818 | 7308121 | 8.79 | 291 | 411 | 31.6 |
| SW14 | 0417459 | 7303966 | 8.76 | 388 | 548 | 31.3 |
| SW15 | 0417454 | 7303966 | 8.94 | 385 | 546 | 30.8 |
| SW16 | 0417533 | 7304004 | 8.90 | 381 | 546 | 31.7 |
| SW17 | 0417576 | 7304014 | 8.90 | 370 | 522 | 31.5 |
| SW18 | 0414907 | 7302548 | 9.26 | 480 | 680 | 31.4 |
| SW19 | 0413521 | 7301377 | 9.54 | 481 | 677 | 30.8 |
| SW20 | 0413481 | 7301286 | 9.49 | 475 | 675 | 33.4 |
| SW21 | 0407429 | 7297056 | 9.93 | 538 | 757 | 33.4 |
| SW22 at Morwa | 0405539 | 7296055 | 9.40 | 65.6 | 92.7 | 32.2 |
| Sw23 | 0396586 | 7280916 | 9.78 | 506 | 712 | 32.7 |

| Sample ID | EASTINGS | NORTHINGS | pH | TDS (ppm) | EC (µS/cm) | TEMPERATURE (ºC) |
|---|---|---|---|---|---|---|
| SW24 | 0401232 | 7282352 | 7.47 | 234 | 329 | 30 |
| SW25 | 0401286 | 7282379 | 7.62 | 327 | 462 | 28.3 |
| SW26 MATEBELE BRIDGE | 0402752 | 7284807 | 7.59 | 330 | 465 | 26.3 |
| SW27 | 0402779 | 7284792 | 8.61 | 387 | 546 | 32.2 |
| SW28 | 0402678 | 7284766 | 8.18 | 496 | 698 | 31.7 |
| SW29 | 0404930 | 7286096 | 7.95 | 441 | 612 | 29.1 |
| SW30 | 0404877 | 7286225 | 8.03 | 430 | 607 | 27.5 |
| SW31 | 0400579 | 7296688 | 8.53 | 143 | 202 | 29.1 |
| SW32 | 0401209 | 7296595 | 8.36 | 53.7 | 61.1 | 28.9 |
| SW33 | 0424084 | 7312321 | 9.56 | 80.1 | 113.4 | 32 |
| sw34 Gaborone dam | 391759 | 7267447 | 7.48 | 132 | 186.9 | 29.9 |
| sw35 | 396500 | 7278820 | 8.53 | 316 | 446 | 26.3 |
| sw37 Segoditshane bridge | 391622 | 7274705 | 8.23 | 347 | 486 | 27 |
| sw38 | 391966 | 7270076 | 7.83 | 96.6 | 136.2 | 25.1 |
| sw39 | 391791 | 7269834 | 8.3 | 435 | 615 | 24.7 |
| sw40 Riverwalk bridge | 392715 | 7270374 | 7.65 | 127 | 178.4 | 26.5 |
| sw41 | 393356 | 7271266 | 7.72 | 123 | 174 | 25 |
| sw42 | 393581 | 9273423 | 7.53 | 77.1 | 108.1 | 27.3 |
| MINIMUM | | | 7.47 | 47.3 | 61.1 | 24.7 |
| MEAN | | | 8.56 | 279.4 | 391.8 | 29.91 |

| Sample ID | EASTINGS | NORTHINGS | pH | TDS (ppm) | EC (µS/cm) | TEMPERATURE (ºC) |
|---|---|---|---|---|---|---|
| MAXIMUM | | | 9.93 | 538 | 757 | 36.3 |

Table 3. Treated wastewater in situ parameters.

| Sample ID | EASTINGS | NORTHINGS | pH | TDS | EC (µS/cm) | TEMPERATURE (ºC) |
|---|---|---|---|---|---|---|
| SW36 | 395707 | 7278163 | 7.65 | 557 | 785 | 28 |

Table 4. Groundwater in situ parameters.

| Sample ID | EASTINGS | NORTHINGS | PH | TDS (ppm) | Ec µs/cm | TEMPERATURE ºC |
|---|---|---|---|---|---|---|
| Z1 | 468223 | 7339764 | 8.94 | 354 | 499 | 31.7 |
| Z2 | 469101 | 7347403 | 9.44 | 1300.2 | 1817 | 31.9 |
| Z3 | 464575 | 7346182 | 7.4 | 1490 | 2137 | 33.5 |
| Z4 | 458008 | 7343962 | 7.4 | 8303 | 11890 | 30.1 |
| Z5 | 459939 | 7338895 | 9.4 | 443 | 624 | 29 |
| Z6 | 413307 | 7315860 | 7.53 | 1080 | 1509 | 33.6 |
| Z7 | 418547 | 7308288 | 8.31 | 1660.4 | 2372 | 25.9 |
| Z8 | 420250 | 7309750 | 6.93 | 114 | 160 | 24.3 |
| Z9 | 421867 | 7310241 | 8.64 | 560 | 790 | 31.1 |
| Z10 | 401411 | 7294023 | 6.98 | 10070 | 14390 | 31 |
| Z11 | 401094 | 7295345 | 8.12 | 5300 | 6550 | 32 |
| Z12 | 409827 | 7296933 | 7.6 | 837 | 1180 | 29.7 |
| Z13 | 398710 | 7285335 | 8.46 | 987 | 987 | 29.1 |
| Z14 | 400828 | 7283154 | 7.92 | 2640 | 3920 | 29.7 |

| Sample ID | EASTINGS | NORTHINGS | PH | TDS (ppm) | Ec us/cm | TEMPERATURE ºC |
|---|---|---|---|---|---|---|
| Z15 | 400348 | 7285576 | 6.82 | 6119 | 9028 | 30 |
| Minimum | | | 6.82 | 114 | 160 | 24.3 |
| Mean | | | 7.99 | 2750.51 | 3856.87 | 30.17 |
| Maximum | | | 9.44 | 10070 | 14390 | 33.6 |

### *4.1.3 Alkalinity*

Alkalinity is a chemical measurement of water's ability to neutralize acids. Alkalinity is also a measure of water's buffering capacity or its ability to resist changes in pH upon the addition of acids or bases. The computed alkalinity of surface water (Table 6) ranges from 25.92 to 242.69 mg/l of $CaCO_3$ with mean value of 125.96 mg/l of $CaCO_3$. The alkalinity of treated wastewater (Table 7) is 186.51 mg/l of $CaCO_3$. The computed alkalinity of the groundwater (Table 8) is ranging from 43.31 to 1208.53 mg/l of $CaCO_3$ having mean value of 273.17 mg/l of $CaCO_3$.

### *4.1.4 Hardness*

Water hardness is the traditional measure of the capacity of water to react with soap, hard water requiring considerably more soap to produce lather. The hardness or softness of water varies from place to place and reflects the nature of the geological properties of the area with which water have been in contact. In general surface waters are softer than ground waters, although this is not always the case (Napacho & Manyele, 2010).

Table 5 below shows the general water hardness classification scale as calcium carbonate (Freeze and Cherry, 1979).

Table 5. Hardness scale.

| HARDNES SCALE | |
|---|---|
| Soft | 0-60 mg/l |
| Moderately hard | 61-120mg/l |
| Hard | 121-180 mg/l |
| Very hard | more than 180mg/l |

The computed hardness of the surface water (Table 6) ranges from 23.19 to 338.05 mg/l of $CaCO_3$ with mean value of 98.22 mg/l of $CaCO_3$. 56% of the total surface water samples have a

hardness of less than 99 mg/l of $CaCO_3$, 37% have hardness between 99 and 200 mg/l of $CaCO_3$ and seven percent have greater than 200 mg/l of $CaCO_3$. In overall the surface water is moderately hard. Treated wastewater hardness (Table 7) is 161.12 mg/l of $CaCO_3$ which is classified as hard. Hardness in the groundwater (Table 8) of the catchment ranges from 47.46 to 5295.26 mg/l of $CaCO_3$ with mean value of 1280.69 mg/l of $CaCO_3$. With the exception of one sample (Z8) which is soft, the groundwater of the catchment is hard to very hard.

Table 6. Surface water Hardness and Alkalinity.

| Sample ID | HARDNESS (CaCO3)mg/l | ALKALINITY (CaCO3) mg/l |
|---|---|---|
| SW1 | 46.35 | 73.8 |
| SW2 | 42.02 | 78.24 |
| SW3 | 27.84 | 96.37 |
| SW4 | 158.94 | 151.16 |
| SW5 | 338.05 | 124.96 |
| SW6 | 43.1 | 98.09 |
| SW7 | 162.98 | 82.83 |
| SW8 | 40.43 | 35.43 |
| SW9 | 272 | 141.73 |
| SW10 | 105.68 | 136.23 |
| SW11 | 161.36 | 137.95 |
| SW12 | 51 | 70.95 |
| SW13 | 48.62 | 127.62 |
| SW14 | 157.48 | 190.8 |
| SW15 | 64.62 | 185.36 |
| SW16 | 94.44 | 182.9 |
| SW17 | 83.15 | 182 |
| SW18 | 149.08 | 230.96 |
| SW19 | 100.11 | 217.84 |
| SW20 | 135.72 | 209.29 |
| SW21 | 138.42 | 231.54 |
| SW22 | 37.78 | 38.47 |
| SW23 | 78.43 | 206.69 |
| SW24 | 66.06 | 125.08 |
| SW25 | 84.34 | 83.82 |
| SW26 | 33.82 | 84.89 |
| SW27 | 114 | 146.98 |
| SW28 | 109.78 | 188.08 |

| Sample ID | HARDNESS (CaCO3)mg/l | ALKALINITY (CaCO3) mg/l |
|---|---|---|
| SW29 | 128.92 | 128.28 |
| SW30 | 100.7 | 133.12 |
| SW31 | 63.1 | 87.56 |
| SW32 | 23.19 | 25.92 |
| SW33 | 39.3 | 51.43 |
| SW34 | 60.65 | 76.85 |
| SW35 | 212.49 | 148.94 |
| SW37 | 151.86 | 242.69 |
| SW38 | 39.64 | 44.04 |
| SW39 | 108.2 | 169.37 |
| SW40 | 58.26 | 76.03 |
| SW41 | 57 | 74.06 |
| SW42 | 38 | 46.01 |
| minimum | 23.19 | 25.92 |
| mean | 98.22 | 125.96 |
| maximum | 338.05 | 242.69 |

Table 7. Treated wastewater hardness and Alkalinity.

| Sample ID | HARDNESS (CaCO3)mg/l | ALKALINITY (CaCO3) mg/l |
|---|---|---|
| SW36 | 161.12 | 186.51 |

Table 8. Groundwater hardness and alkalinity.

| Sample ID | HARDNESS (CaCO3)mg/l | ALKALINITY (CaCO3) mg/l |
|---|---|---|
| Z1 | 171.23 | 170.9 |
| Z2 | 358.05 | 64.88 |
| Z3 | 392.18 | 239.82 |
| Z4 | 4322.91 | 137.71 |
| Z5 | 172.51 | 238.65 |
| Z6 | 408.14 | 174.12 |
| Z7 | 275.96 | 1208.53 |
| Z8 | 47.46 | 43.31 |
| Z9 | 253.99 | 217.76 |
| Z10 | 5295.26 | 137.71 |

| | | |
|---|---|---|
| Z11 | 2441.92 | 157.64 |
| Z12 | 371.59 | 276.65 |
| Z13 | 384.88 | 259.18 |
| Z14 | 1298.9 | 474.06 |
| Z15 | 3015.38 | 296.58 |
| Minimum | 47.46 | 43.31 |
| Mean | 5295.26 | 273.17 |
| Maximum | 1280.69 | 1208.53 |

### 4.2 Water type

Fifteen types of water are recognized in the surface water of the study area (Table 9): Na-$HCO_3$-Cl (24.4%), Na-Mg-$HCO_3$-Cl (14.6%), Ca-Mg-Na-HCO3 (9.8%), Mg-Na-Ca-HCO3 (7.3%), Ca-Mg-HCO3 (7.3%), Na-HCO3 (4.9%), Na-Mg-Ca-HCO3 (4.9%), Mg-Ca-Na-HCO3 (4.9%), Na-Mg-Ca-HCO3-Cl (4.9%), Ca-Mg-HCO3-Cl (4.9%), Mg-Ca-HCO3 (2.4%), Na-HCO3-Cl-SO4 (2.4%), Ca-Na-HCO3 (2.4%), Na-HCO3-CO3 (2.4%), and Na-Mg-CO3 (2.4%). Treated water is Na-Mg-HCO3-Cl type (Table 10).

Thirteen types of groundwater are identified in the study area (Table 11): Mg-Na-HCO3 (6.7 %), Na-Mg-Cl (6.7%), Na-Cl-HCO3 (6.7 %), Mg-Na-Ca-Cl (6.7 %), Na-Mg-HCO3-Cl (6.7 %), Na-Ca-Mg-SO4-Cl-HCO3 (6.7 %), Mg-HCO3 (6.7 %), Ca-Mg-HCO3-NO3 (6.7 %), Mg-Na-HCO3-Cl (6.7 %), Mg-Ca-Na-Cl (13 %), Mg-Cl-HCO3 (13 %), Na-Mg-Cl-HCO3 (6.7) and Mg-Ca-Cl (6.7 %). The relative dominant groundwater types are Mg-Ca-Na-Cl from borehole Z10 and Z15, Mg-Cl-HCO3 from borehole Z12 and Z14. Borehole Z10 and Z15 are located on igneous and metamorphic rocks respectively, While boreholes Z12 and Z14 are located on metamorphic (Archaean gneiss) and igneous (Gaborone granite) rocks, respectively, whereas the rest of the boreholes are downstream and located on the metamorphic and sedimentary rock types.

In all the waters the dominant cation is $Na^+$. In both the surface water and treated wastewater the dominant anion is $HCO3^-$ whereas in groundwater is $Cl^-$.

Table 9. Surface water types.

| Sample ID | WATER TYPE |
|---|---|
| SW1 | Na-Mg-CO3 |
| SW2 | Na-HCO3-CO3 |
| SW3 | Na-HCO3 |

| | |
|---|---|
| SW4 | Mg-Na-Ca-HCO3 |
| SW5 | Ca-Na-HCO3 |
| SW6 | Na-HCO3 |
| SW7 | Mg-Na-Ca-HCO3 |
| SW8 | Ca-Mg-Na-HCO3 |
| SW9 | Mg-Na-Ca-HCO3 |
| SW10 | Na-Mg-HCO3-Cl |
| SW11 | Na-Mg-Ca-HCO3 |
| SW12 | Mg-Ca-Na-HCO3 |
| SW13 | Na-HCO3-Cl |
| SW14 | Na-Mg-HCO3-Cl |
| SW15 | Na-HCO3-Cl |
| SW16 | Na-Mg-HCO3-Cl |
| SW17 | Na-HCO3-Cl |
| SW18 | Na-HCO3-Cl |
| SW19 | Na-HCO3-Cl |
| SW20 | Na-HCO3-Cl |
| SW21 | Na-HCO3-Cl |
| SW22 | Ca-Mg-Na-HCO3 |
| SW23 | Na-HCO3-Cl |
| SW24 | Na-Mg-Ca-HCO3-Cl |
| SW25 | Na-Mg-HCO3-Cl |
| SW26 | Na-HCO3-Cl-SO4 |
| SW27 | Na-Mg-HCO3-Cl |
| SW28 | Na-HCO3-Cl |
| SW29 | Na-Mg-Ca-HCO3-Cl |
| SW30 | Na-Mg-HCO3-Cl |
| SW31 | Na-Mg-Ca-HCO3 |
| SW32 | Ca-Mg-HCO3 |
| SW33 | Mg-Ca-HCO3 |
| SW34 | Mg-Ca-Na-HCO3 |
| SW35 | Ca-Mg-HCO3-Cl |
| SW37 | Ca-Mg-HCO3 |
| SW38 | Ca-Mg-HCO3-Cl |
| SW39 | Na-HCO3-Cl |
| SW40 | Ca-Mg-Na-HCO3 |
| SW41 | Ca-Mg-Na-HCO3 |
| SW42 | Ca-Mg-HCO3 |

Table 10. Treated wastewater water type.

| Sample ID | WATER TYPE |
|---|---|
| SW36 | Na-Mg-HCO3-Cl |

Table 11. Groundwater water types.

| Sample ID | WATER TYPE |
|---|---|
| Z1 | Mg-Na-HCO3 |
| Z2 | Na-Mg-Cl |
| Z3 | Na-Cl-HCO3 |
| Z4 | Mg-Na-Ca-Cl |
| Z5 | Na-Mg-HCO3-Cl |
| Z6 | Na-Ca-Mg-SO4-Cl-HCO3 |
| Z7 | Mg-HCO3 |
| Z8 | Ca-Mg-HCO3-NO3 |
| Z9 | Mg-Na-HCO3-Cl |
| Z10 | Mg-Ca-Na-Cl |
| Z11 | Mg-Ca-Na-Cl |
| Z12 | Mg-Cl-HCO3 |
| Z13 | Na-Mg-Cl-HCO3 |
| Z14 | Mg-Cl-HCO3 |
| Z15 | Mg-Ca-Cl |

Figures 18 and 19 below show the piper diagram for surface water and treated wastewater and groundwater respectively. Fig. 18 shows that in the anion triangle all samples are concentrated towards HCO3 indicating the dominancy of this species in the surface water and treated wastewater whereas Fig. 19 shows that dominant anion in the groundwater is Cl. As for the cation in the surface water and treated wastewater, samples are clustered towards calcium and a combination of sodium and potassium, with a dominancy of Na + K (Fig. 18). The diamond plot shows that the majority of the surface water samples and a treated wastewater sample lie below 40% of Ca and Mg. As for the cation in the groundwater, samples are clustered towards a combination of sodium and potassium and magnesium end, with dominant number of samples toward the combination of sodium and potassium (Fig. 19).

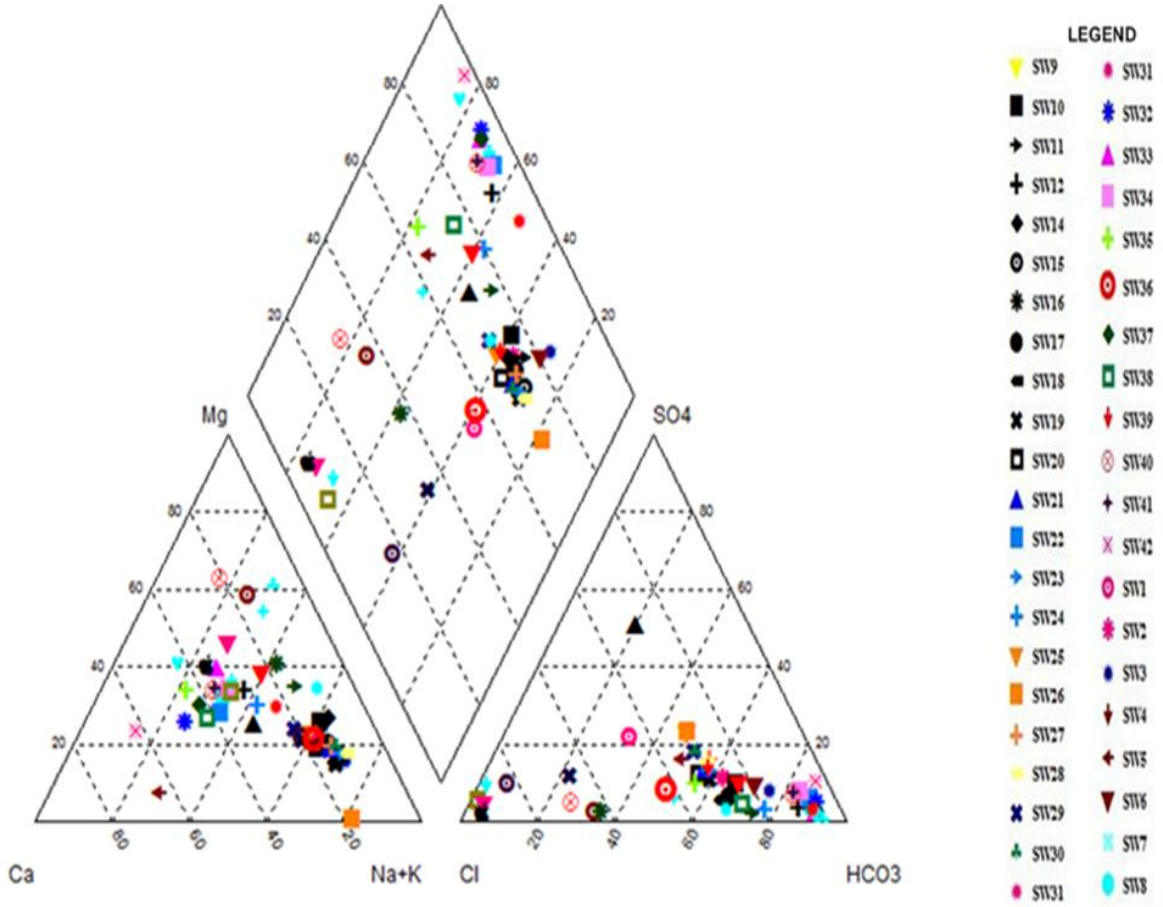


Figure 18. Surface water and treated wastewater (SW36) piper diagram.

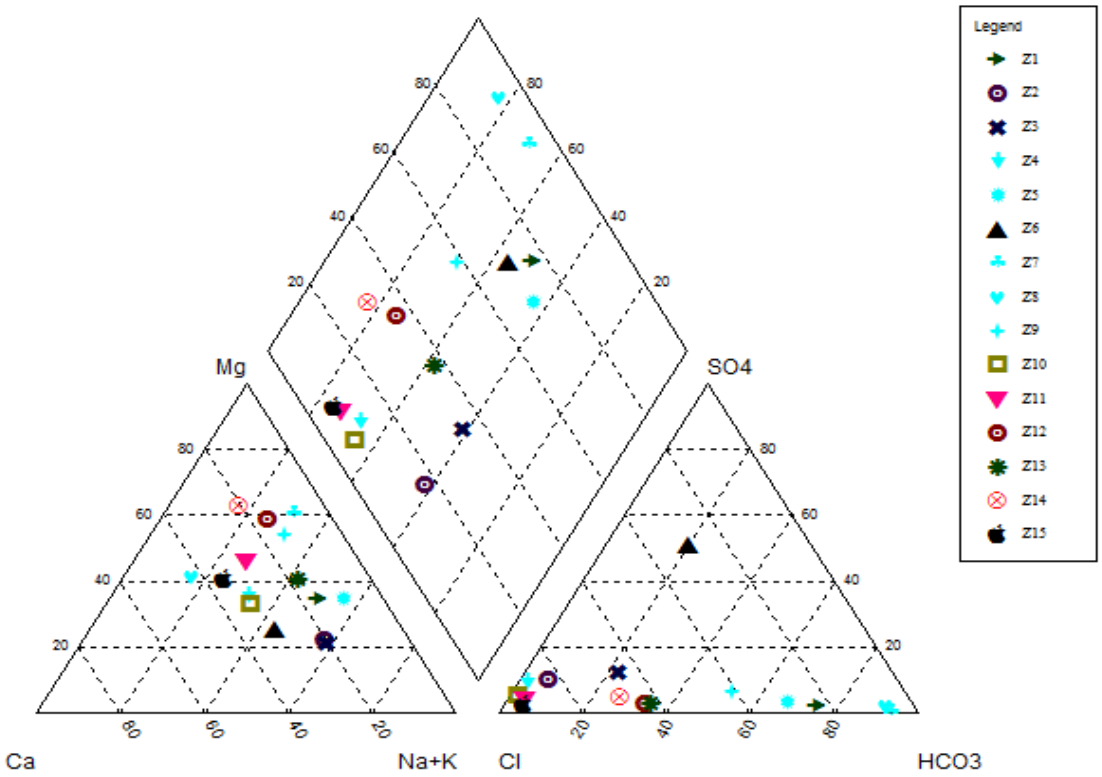


Figure 19. Groundwater piper diagram.

## 4.3 Major Ions

### *4.3.1 Cations*

As it is shown in the Tables (12, 13 & 14 ) below, the surface water of the study area were analyzed for $Ca^{2+}$, $Mg^{2+}$, $Na^{+}$, $K^{+}$ and $Li^{+}$ ions. The concentration of $Ca^{2+}$ ranges from 4.80 to 121.76 mg/l with mean value of 19.27 mg/l while the concentration $Mg^{2+}$ ranges from 1.95 to 42.08 mg/l with mean value of 12.42 mg/l. The average concentration of $Na^{+}$ ions in the surface water is 50.86 mg/l. Highest value (139.18mg/l) was found at the SW11 while the minimum value (0.91 mg/l) was found at the SW41 (42). $K^{+}$ range from 3.61 mg/l to 35.31 mg/l and $Li^{+}$ ranges from 0.00 to 2.43 mg/l with mean values of 13.63 mg/l and 0.07 mg/l respectively. In the treated water the concentration of $Ca^{2+}$, $Mg^{2+}$, $Na^{+}$, $K^{+}$ and $Li^{+}$ is 29.46 mg/l, 21.26, 107.98 mg/l, 17.28 mg/l and 0.002 mg/l, respectively. The results of the groundwater cations analyses revealed that $Ca^{2+}$ range from 9.67 mg/l to 1051.8 mg/l and $Mg^{2+}$ ranges from 5.66 mg/l to 648 mg/l with mean value of 221.22 mg/l and 176.76 mg/l, respectively, while $Na^{+}$ ranges from 1.47

mg/l to 1198.6 mg/l and $K^+$ ranges from 2.27 to 103.56 mg/l with an average value of 274.94 mg/l and 23.61 mg/l, respectively. The average concentration of $Li^+$ is 0.10 mg/l and the highest concentration (0.46 mg/l) is measured in the sample Z10 and the lowest (0.0005mg/l) is in the sample Z8.

In all the waters, surface water, treated wastewater and groundwater, based on the mean values of the chemical parameters, the cations were in the order of abundance as $Na^+ > Ca^{2+} > Mg^{2+} > K^+ > Li^+$.

Table 12. Surface water cations (mg/l).

| Sample ID | Calcium (Ca) | Potassium (K) | Lithium (Li) | Magnesium (Mg) | Sodium (Na) |
|---|---|---|---|---|---|
| SW1 | 8.396 | 12.246 | 0.069 | 6.159 | 28.94 |
| SW2 | 7.968 | 10.84 | 0.024 | 5.37 | 27.12 |
| SW3 | 4.802 | 10.466 | 0.008 | 3.854 | 27.38 |
| SW4 | 22.32 | 17.552 | 0.01 | 25.06 | 47.24 |
| SW5 | 121.76 | 13.18 | 0.014 | 8.43 | 53.37 |
| SW6 | 7.578 | 11.38 | 0.001 | 5.874 | 42.03 |
| SW7 | 24.4 | 6.596 | 0.012 | 24.78 | 30.24 |
| SW8 | 8.52 | 6.613 | 0.0008 | 4.647 | 5.017 |
| SW9 | 39.64 | 23.26 | 0.004 | 42.08 | 68.78 |
| SW10 | 14.582 | 16.318 | 0.004 | 16.818 | 65.48 |
| SW11 | 29.72 | 16.306 | 0.03 | 21.16 | 139.18 |
| SW12 | 9.392 | 8.415 | 0.0009 | 6.69 | 8.99 |
| SW13 | 8.466 | 27.9 | 0.0015 | 6.672 | 53.58 |
| SW14 | 18.574 | 18.104 | 0.008 | 26.98 | 109.42 |
| SW15 | 10.722 | 15.436 | 0.004 | 9.186 | 62.46 |
| SW16 | 15.852 | 17.738 | 0.004 | 13.324 | 66.42 |
| SW17 | 13.72 | 16.278 | 0.002 | 11.866 | 64.72 |
| SW18 | 29.802 | 35.31 | 0.018 | 18.126 | 137.79 |
| SW19 | 20.3 | 18.62 | 0.004 | 12 | 99.2 |
| SW20 | 26.1 | 19.93 | 0.006 | 17.128 | 95.74 |
| SW21 | 23.24 | 22.54 | 0.004 | 19.522 | 117.1 |
| SW22 | 8.67 | 4.552 | 0.0005 | 3.91 | 6.235 |
| SW23 | 12.788 | 16.16 | 0.004 | 11.286 | 76.56 |
| SW24 | 12.956 | 8.158 | 0.002 | 8.398 | 17.678 |

| Sample ID | Calcium (Ca) | Potassium (K) | Lithium (Li) | Magnesium (Mg) | Sodium (Na) |
|---|---|---|---|---|---|
| SW25 | 14.886 | 15.022 | 0.004 | 11.448 | 48 |
| SW26 | 13.258 | 15.976 | 0.006 | 10.172 | 61.2 |
| SW27 | 18.586 | 19.274 | 0.08 | 16.41 | 95.14 |
| SW28 | 16.622 | 23.68 | 0.198 | 16.578 | 113.38 |
| SW29 | 24.48 | 15.714 | 2.426 | 16.46 | 63.06 |
| SW30 | 15.852 | 18.454 | 0.008 | 14.784 | 87.72 |
| SW31 | 11.068 | 7.488 | 0.002 | 8.612 | 22.08 |
| SW32 | 6.069 | 3.985 | 0.0011 | 1.954 | 1.328 |
| SW33 | 7.129 | 8.017 | 0.002 | 5.224 | 2.042 |
| SW34 | 11.9 | 6.137 | 0.0005 | 7.505 | 9.892 |
| SW35 | 48.15 | 11.43 | 0.004 | 22.4 | 21 |
| SW37 | 35.58 | 8.246 | 0.002 | 15.302 | 21.32 |
| SW38 | 9.772 | 7.288 | 0.0017 | 3.702 | 3.969 |
| SW39 | 21.56 | 10.91 | 0.008 | 13.2 | 67.04 |
| SW40 | 12.13 | 4.727 | 0.0007 | 6.787 | 8.347 |
| SW41 | 11.76 | 4.798 | 0.0006 | 6.707 | 8.093 |
| SW42 | 11.11 | 3.606 | 0.0019 | 2.488 | 0.9137 |
| MINIMUN | 4.802 | 3.606 | 0.0005 | 1.954 | 0.9137 |
| MEAN | 19.27 | 13.63 | 0.073 | 12.42 | 50.86 |
| MAXIMUM | 121.76 | 35.31 | 2.43 | 42.08 | 139.18 |

Table 13. Treated wastewater (mg/l).

| Sample ID | Calcium (Ca) | Potassium (K) | Lithium (Li) | Magnesium (Mg) | Sodium (Na) |
|---|---|---|---|---|---|
| SW36 | 29.46 | 17.278 | 0.002 | 21.26 | 107.98 |

Table 14. Groundwater cations (mg/l).

| Sample ID | Calcium (Ca) | Potassium (K) | Lithium (Li) | Magnesium (Mg) | Sodium (Na) |
|---|---|---|---|---|---|
| Z1 | 21.14 | 45.57 | 0.004 | 28.76 | 51.18 |
| Z2 | 68.74 | 12.896 | 0.06 | 45.26 | 217.2 |
| Z3 | 77.92 | 9.468 | 0.068 | 47.98 | 248.6 |
| Z4 | 816.3 | 38.69 | 0.18 | 554.7 | 943.2 |
| Z5 | 13.548 | 8.348 | 0.012 | 32.46 | 94.84 |
| Z6 | 89.52 | 9.708 | 0.14 | 44.82 | 142.5 |
| Z7 | 12.85 | 17.75 | 0.0066 | 59.22 | 46.85 |
| Z8 | 9.671 | 4.698 | 0.0005 | 5.662 | 1.467 |
| Z9 | 21.3 | 3.126 | 0.014 | 48.76 | 52.66 |
| Z10 | 1051.8 | 103.56 | 0.46 | 648 | 1198.6 |
| Z11 | 362.4 | 8.556 | 0.099 | 373.2 | 408.9 |
| Z12 | 31.98 | 2.27 | 0.024 | 70.84 | 57.52 |
| Z13 | 46.8 | 5.3 | 0.104 | 65.08 | 142.24 |
| Z14 | 127.98 | 7.244 | 0.05 | 237.8 | 115 |
| Z15 | 566.3 | 77 | 0.33 | 388.8 | 403.3 |
| Minimum | 9.671 | 2.27 | 0.0005 | 5.662 | 1.467 |
| Average | 221.217 | 23.612 | 0.103 | 176.756 | 274.937 |
| Maximum | 1051.8 | 103.56 | 0.46 | 648 | 1198.6 |

### *4.3.2 Anions*

In all the water samples $Cl^-$, $SO_4^{2-}$, $HCO_3^-$, $PO_4^{3-}$, $CO_3^{2-}$, $NO_3^-$and $F^-$ were analysed (Table 15). In surface water the concentrations of $HCO_3^-$ ranges from 18.40 mg/l to 295.90 mg/l with mean value of 148.15 mg/l while the measured concentrations of $CO_3^{2-}$ ion ranges from 0 mg/l to 35.20 mg/l with an average concentration of 2.67 mg/l. The concentrations of $Cl^-$ ions range from 0.97 mg/l to 85.7 mg/l with mean value of 33.92 mg/l while the concentration of $SO_4^{2-}$ ions range from 1.33 mg/l to 52.41 mg/l with mean values of 18.91 mg/l. $NO_3^-$ concentration ranges from 0.23 mg/l to 52.41 mg/l with mean value of 10.08 mg/l. The average concentration of $F^-$ ion is

0.49 mg/l and the highest concentration (1.02 mg/l) was measured in sample SW31 whereas the lowest measured concentration (0.20 mg/l) was measured in SW41. The concentrations of $PO_4^{3-}$ ion ranges from 0 mg/l to 149 mg/l with mean value of 5.07 mg/l. The measured concentration of $HCO_3^-$, $CO_3^{2-}$, $Cl^-$, $SO_4^{2-}$, $NO_3^-$, $F^-$ and $PO_4^{3-}$ in the treated wastewater (Table 16) was 227.4mg/l, 0 mg/l, 114.07mg/l, 28.7 mg/l, 32.21 mg/l, 0.35 mg/l and 9.53 mg/l, respectively.

In the analysed groundwater (Table 17), the concentration of $HCO_3^-$ ranges from 52.8 mg/l to 1473.5 mg/l with mean value of 329.68 mg/l while the concentration $CO_3^{2-}$ range from 0 mg/l to 13.9 mg/l with mean value of 1.66 mg/l. The average concentration of $Cl^-$ ion is 1322.50 mg/l and the highest concentration of $Cl^-$ (5886.33 mg/l) ion was measured in the sample Z10 whereas the lowest concentration (2.29 mg/l) was measured in the sample Z8. The concentrations of $SO_4^{2-}$ ion is ranging from 0.88 mg/l to 657.25 mg/l with mean value of 146.38 while $NO_3^-$ concentrations range from 0.71 mg/l to 424.84 mg/l with mean value of 60.67 mg/l. The average concentration of $F^-$ ion is 0.89 mg/l and the highest measured concentration (3.53 mg/l) was measured in the sample Z10 while the lowest measured concentration (0 mg/l) was in sample Z4. The concentration of $PO_4^{3-}$ ranges from 0 mg/l to 1.07 mg/l with mean value of 0.13 mg/l.

Based on the mean values of the chemical parameters, in the surface water the anions were in the order of abundance as $HCO_3^- > Cl^- > SO_4^{2-} > NO_3^- > PO_4^{3-} > F^- > CO_3^{2-}$, in the treated water $HCO_3^- > Cl^- > NO_3^- > SO_4^{2-} > PO_4^{3-} > F^- > CO_3^{2-}$ while in the groundwater the anions reveal order of abundance as $Cl^- > HCO_3^- > SO_4^{2-} > NO_3^- > CO_3^{2-} > F^- > PO_4^{3-}$.

In the groundwater, the measured concentration of $Cl^-$ and $NO_3^-$ is much greater than the measured concentrations of these ions both in the surface and treated water whereas the measured concentration of $PO_4^{3-}$ in the groundwater is significantly less than the measured concentration of $PO_4^{3-}$ in both surface water and treated water. The highest measured concentration of $PO_4^{3-}$ (9.53 mg/l) is in the treated wastewater.

Table 15. Surface water anions (mg/l).

| Sample ID | Cl | SO4 | NO3 | F | CO3 | HCO3 | PO4 |
|---|---|---|---|---|---|---|---|
| sw1 | 14.83 | 9.51 | 0.64 | 0.51 | 35.2 | 18.4 | 0 |
| sw2 | 14.72 | 8.52 | 1.76 | 0.51 | 17.5 | 59.8 | 0 |
| sw3 | 14.72 | 9.51 | 0.93 | 0.39 | 0 | 117.5 | 0 |
| sw4 | 35.06 | 11.13 | 17.79 | 0.59 | 0 | 184.3 | 0 |
| sw5 | 41.7 | 25.41 | 0.64 | 0.56 | 25.4 | 100.7 | 0 |
| sw6 | 18.33 | 11.79 | 0.32 | 0.54 | 0 | 119.6 | 0 |
| sw7 | 1.36 | 1.65 | 0.73 | 0.41 | 5.7 | 89.4 | 0 |
| sw8 | 2.11 | 1.33 | 0.28 | 0.38 | 0 | 43.2 | 0 |
| sw9 | 34.66 | 19.22 | 0.9 | 0.53 | 0 | 172.8 | 0 |
| sw10 | 34.63 | 19.45 | 2.1 | 0.5 | 0 | 166.1 | 0.09 |
| sw11 | 34.43 | 19.71 | 1.01 | 0.47 | 0 | 168.2 | 0.02 |
| sw12 | 6.15 | 2.87 | 5.51 | 0.7 | 0 | 86.5 | 0 |
| sw13 | 33.99 | 19.1 | 5.34 | 0.49 | 0 | 155.6 | 0.04 |
| sw14 | 53.29 | 16.17 | 3.66 | 0.55 | 6.8 | 218.8 | 0 |
| sw15 | 53.8 | 17.04 | 8.5 | 0.54 | 0 | 226 | 0.42 |
| sw16 | 53.25 | 16.67 | 8.56 | 0.52 | 0 | 223 | 0.29 |
| sw17 | 52.89 | 16.17 | 12.91 | 0.53 | 0 | 221.9 | 0.28 |
| sw18 | 75.45 | 17.62 | 20.78 | 0.61 | 0 | 281.6 | 1.26 |
| sw19 | 78.13 | 37.28 | 1.22 | 0.64 | 0 | 265.6 | 0.82 |
| sw20 | 74.79 | 38.21 | 0.23 | 0.61 | 17 | 220.6 | 0.82 |
| sw21 | 85.7 | 52.41 | 13.46 | 0.54 | 0 | 282.3 | 3 |
| sw22 | 2 | 2.52 | 1.27 | 0.52 | 0 | 46.9 | 0 |
| sw23 | 73.4 | 45.45 | 7.55 | 0.34 | 0 | 252 | 4.41 |
| sw24 | 22.65 | 4.36 | 5.51 | 0.25 | 0 | 152.5 | 0.48 |
| sw25 | 37.38 | 38.12 | 36.11 | 0.47 | 0 | 102.2 | 6.46 |
| sw26 | 37.76 | 40.02 | 39.64 | 0.47 | 0 | 103.5 | 6.21 |
| sw27 | 50.32 | 39.07 | 24.18 | 0.54 | 0 | 179.2 | 4.35 |

| Sample ID | Cl | SO4 | NO3 | F | CO3 | HCO3 | PO4 |
|---|---|---|---|---|---|---|---|
| sw28 | 68.59 | 47.56 | 31.14 | 0.45 | 0 | 229.3 | 5.75 |
| sw29 | 54.28 | 43.34 | 50.42 | 0.5 | 0 | 156.4 | 10.75 |
| sw30 | 54.28 | 43.2 | 43.46 | 0.49 | 0 | 162.3 | 10.28 |
| sw31 | 4.74 | 2.83 | 0.76 | 1.02 | 1.8 | 103.1 | 0 |
| sw32 | 1.11 | 1.36 | 4.6 | 0.2 | 0 | 31.6 | 0.3 |
| sw33 | 2.52 | 1.34 | 5.07 | 0.51 | 0 | 62.7 | 0 |
| sw34 | 5.29 | 6.78 | 2.63 | 0.52 | 0 | 93.7 | 0 |
| sw35 | 63.93 | 24.61 | 6.9 | 0.36 | 0 | 181.6 | 0.62 |
| sw37 | 12.26 | 5.73 | 6.79 | 0.36 | 0 | 295.9 | 0.23 |
| sw38 | 10.93 | 2.56 | 5.88 | 0.26 | 0 | 53.7 | 2.16 |
| sw39 | 61.17 | 38.07 | 31.62 | 0.56 | 0 | 206.5 | 1.49 |
| sw40 | 6.77 | 6.04 | 0.27 | 0.45 | 0 | 92.7 | 0 |
| sw41 | 6.51 | 6.25 | 0.31 | 0.47 | 0 | 90.3 | 0 |
| sw42 | 0.97 | 5.14 | 1.86 | 0.2 | 0 | 56.1 | 0 |
| Minimum | 0.97 | 1.33 | 0.23 | 0.2 | 0 | 18.4 | 0 |
| Mean | 33.92 | 18.91 | 10.08 | 0.49 | 2.67 | 148.15 | 5.07 |
| Maximum | 85.7 | 52.41 | 50.42 | 1.02 | 35.2 | 295.9 | 10.75 |

Table 16. Treated wastewater anions (mg/l).

| Sample ID | Cl | SO4 | NO3 | F | CO3 | HCO3 | PO4 |
|---|---|---|---|---|---|---|---|
| sw36 | 114.07 | 28.7 | 32.21 | 0.35 | 0 | 227.4 | 9.53 |

Table 17. Groundwater anions (mg/l).

| Sample ID | Cl | $SO_4$ | $NO_3$ | F | $CO_3$ | $HCO_3$ | $PO_4$ |
|---|---|---|---|---|---|---|---|
| Z1 | 32.48 | 4.17 | 25.45 | 0.28 | 13.9 | 180.1 | 0.21 |
| Z2 | 530.59 | 84.66 | 2.17 | 0.38 | 0 | 79.1 | 0 |
| Z3 | 501.31 | 122.03 | 22.23 | 0.42 | 0 | 292.4 | 0 |
| Z4 | 4599.45 | 657.25 | 0.71 | 0 | 0 | 167.9 | 0 |
| Z5 | 69.53 | 9.98 | 10.96 | 0.45 | 11 | 268.6 | 0 |
| Z6 | 180.88 | 424.46 | 32.06 | 0.5 | 0 | 212.3 | 0 |
| Z7 | 53.82 | 4.09 | 3.65 | 0.26 | 0 | 1473.5 | 1.07 |
| Z8 | 2.29 | 0.88 | 25.96 | 0.16 | 0 | 52.8 | 0.25 |
| Z9 | 122.59 | 24.28 | 54.33 | 0.25 | 0 | 265.5 | 0.29 |
| Z10 | 5886.33 | 471.81 | 36.35 | 3.53 | 0 | 167.9 | 0 |
| Z11 | 2398.26 | 158.95 | 424.84 | 0.98 | 0 | 192.2 | 0 |
| Z12 | 374.19 | 20.48 | 3.78 | 2.18 | 0 | 337.3 | 0 |
| Z13 | 332.2 | 18.72 | 3.53 | 2.18 | 0 | 316 | 0 |
| Z14 | 867.99 | 81.26 | 33.78 | 0.59 | 0 | 578 | 0 |
| Z15 | 3885.62 | 112.7 | 230.52 | 1.16 | 0 | 361.6 | 0 |
| Minimum | 2.29 | 0.88 | 0.71 | 0 | 0 | 52.8 | 0 |
| Average | 1322.50 | 146.38 | 60.67 | 0.89 | 1.66 | 329.68 | 0.13 |
| Maximum | 5886.33 | 657.25 | 424.84 | 3.53 | 13.9 | 1473.5 | 1.07 |

### *4.3.2 Trace elements*

Waters samples from the studied area were also analyzed for trace elements. The analyzed trace elements are arsenic (As), barium (Ba), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), manganese (Mn), nickel (Ni), lead (Pb) and zinc (Zn).

The result of trace analyses revealed that in the analyzed surface water (Table 18) nickel (Ni) is the major trace element having mean concentration of 0.34 mg/l followed by iron (0.128 mg/l), lead (0.111 mg/l), and barium (0.069 mg/l). All the other remaining analyzed trace elements were occurred having mean concentration of less than 0.04 mg/l. Among the analyzed trace

elements in the treated wastewater (Table 19) the dominant trace elements is nickel (Ni) with an average concentration of 0.69 mg/l followed by barium (0.0329 mg/l), zinc (0.032 mg/l) and lead (0.028 mg/l). All the other remaining analyzed trace elements have a mean concentration less than 0.008 mg/l. In the groundwater, as shown in the Table 20 the result indicated that among the analyzed trace elements nickel occurred having the highest mean concentration (2.063 mg/l) followed by lead (0.173 mg/l), barium (0.095 mg/l) and manganese (0.043 mg/l). All the remaining analyzed trace elements were found have mean concentration of less than 0.04 mg/l. Based on the mean values of the chemical parameters, the order of abundance of trace elements in the surface water was Ni > Fe > Pb > Ba > Zn > Mn > Cd > As > Co > Cr > Cu, in the treated wastewater Ni > Ba > Zn > Pb > Fe > Cd > Mn > As > Co > Cr and Cu having equal concentration (0 mg/l) while in the groundwater the analyzed trace element reveal order of abundance as Ni > Pb > Ba > Mn > Zn > Fe > Cd > As > Cu > Co > Cr.

In the groundwater with the exception of iron, chromium, cobalt and cadmium, all the remaining analyzed trace elements have a concentration greater than the concentration in the surface and treated wastewater. The highest iron concentration (0.128 mg/l) is in the surface water followed by groundwater (0.015 mg/l) and treated water (0.007 mg/l). The highest concentration of Cr was in the surface water (0.001 mg/l) followed by groundwater (0.0002 mg/l) and treated wastewater (0 mg/l). Cadmium concentration in the groundwater (0.003 mg/l) is less than its concentration in both surface water and treated wastewater (0.004 mg/l). Cobalt is found having equal concentration (0.001 mg/l) in all the analyzed waters.

Table 18. Surface water trace elements (mg/l).

| Sample ID | Arsenic (As) | Barium (Ba) | Cadmium (Cd) | Cobalt (Co) | Chromium (Cr) | Copper (Cu) | Iron (Fe) | Manganese (Mn) | Nickel (Ni) | Lead (Pb) | Zinc (Zn) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| SW1 | 0.0178 | 0.0549 | 0.0161 | 0.0072 | 0.0251 | 0.0119 | 0.4842 | 0.251 | 0.497 | 0.163 | 0.0445 |
| SW2 | 0.0041 | 0.0443 | 0.0077 | 0.0038 | 0.0028 | 0.0008 | 0.6159 | 0.004 | 0.463 | 0.006 | 0.0325 |
| SW3 | 0.0032 | 0.039 | 0.0073 | 0.0024 | 0.0007 | 0 | 0.2617 | 0.2207 | 0.48 | 0.278 | 0.306 |
| SW4 | 0.0028 | 0.0859 | 0.0083 | 0 | 0 | 0 | 0.0026 | 0.376 | 0.564 | 0.01 | 0.01 |
| SW5 | 0.0045 | 0.056 | 0 | 0.0012 | 0.0003 | 0.0004 | 0.0536 | 0.0211 | 0.34 | 0.146 | 0.0036 |
| SW6 | 0.0055 | 0.407 | 0 | 0 | 0.0001 | 0 | 0.0855 | 0.0034 | 0.417 | 0.119 | 0.0097 |
| SW7 | 0.0027 | 0.0429 | 0.0058 | 0 | 0 | 0 | 0.0038 | 0.0015 | 0.475 | 0.018 | 0.0426 |
| SW8 | 0.0066 | 0.547 | 0 | 0.001 | 0.0002 | 0 | 0.174 | 0.0017 | 0.448 | 0.075 | 0.0339 |
| SW9 | 0.0053 | 0.05 | 0.0001 | 0.0015 | 0 | 0.0001 | 0.1357 | 0.0552 | 0.31 | 0.059 | 0.0408 |
| SW10 | 0.0046 | 0.0581 | 0.0055 | 0.0015 | 0 | 0 | 0.0361 | 0.0051 | 0.353 | 0.186 | 0.0307 |
| SW11 | 0.0046 | 0.0384 | 0.0062 | 0.0015 | 0 | 0 | 0.0808 | 0.0186 | 0.247 | 0.266 | 0.0071 |
| SW12 | 0.0015 | 0.0457 | 0.008 | 0 | 0.0002 | 0 | 0.3008 | 0.0024 | 0.338 | 0.018 | 0.0136 |
| SW13 | 0.0001 | 0.021 | 0 | 0.0025 | 0 | 0 | 0.1025 | 0.001 | 0.219 | 0.104 | 0.0067 |
| SW14 | 0.0044 | 0.0689 | 0 | 0.0002 | 0 | 0 | 0.0067 | 0.0157 | 0.398 | 0.293 | 0.0349 |
| SW15 | 0.0012 | 0.0618 | 0.0007 | 0.0029 | 0 | 0 | 0.0002 | 0.0026 | 0.38 | 0.076 | 0.0046 |
| SW16 | 0.0035 | 0.0721 | 0.0033 | 0.0009 | 0 | 0.0003 | 0.0045 | 0.0099 | 0.402 | 0.006 | 0.0329 |
| SW17 | 0.0014 | 0.0673 | 0 | 0.0031 | 0 | 0 | 0.0099 | 0.0011 | 0.416 | 0.247 | 0.0309 |
| SW18 | 0.0049 | 0.0696 | 0.0029 | 0.0006 | 0 | 0 | 0.0138 | 0.002 | 0.425 | 0.113 | 0.0352 |
| SW19 | 0.0048 | 0.055 | 0.0003 | 0.0018 | 0.0003 | 0 | 0.0002 | 0.003 | 0.445 | 0.332 | 0.0159 |
| SW20 | 0.0053 | 0.0532 | 0.0021 | 0.004 | 0.0003 | 0 | 0.0015 | 0.0024 | 0.376 | 0.107 | 0.0001 |
| SW21 | 0.0053 | 0.0405 | 0.0051 | 0.0009 | 0 | 0 | 0.0007 | 0.001 | 0.125 | 0.291 | 0.0335 |
| SW22 | 0.0031 | 0.0283 | 0.0114 | 0 | 0 | 0 | 0.0488 | 0.0008 | 0.369 | 0.226 | 0.0135 |
| SW23 | 0.0035 | 0.017 | 0.0013 | 0.0038 | 0 | 0.0001 | 0.0038 | 0.0004 | 0.131 | 0.068 | 0.0374 |
| SW24 | 0.0006 | 0.0495 | 0.0127 | 0 | 0 | 0 | 0.0249 | 0.0002 | 0.358 | 0.107 | 0.0294 |
| SW25 | 0.0034 | 0.0173 | 0.001 | 0 | 0 | 0 | 0.0754 | 0.001 | 0.498 | 0.016 | 0.0263 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| SW26 | 0.0039 | 0.0161 | 0 | 0.0008 | 0.0005 | 0 | 0.2572 | 0.0021 | 0.491 | 0.041 | 0.0329 |
| SW27 | 0.003 | 0.0319 | 0.0061 | 0.003 | 0 | 0 | 0.009 | 0.0024 | 0.473 | 0.139 | 0.023 |
| SW28 | 0.0045 | 0.0405 | 0 | 0.0009 | 0 | 0.0016 | 0.013 | 0.0003 | 0.614 | 0.152 | 0.0296 |
| SW29 | 0.0007 | 0.0249 | 0.0066 | 0.0014 | 0 | 0.0009 | 0.0169 | 0.002 | 0.54 | 0.133 | 0.022 |
| SW30 | 0.0016 | 0.0256 | 0.0044 | 0.0026 | 0 | 0 | 0.0538 | 0.0858 | 0.501 | 0.078 | 0.0325 |
| SW31 | 0.0017 | 0.0483 | 0 | 0 | 0 | 0 | 0.0093 | 0.0018 | 0.487 | 0.042 | 0.0024 |
| SW32 | 0.0006 | 0.0193 | 0.0056 | 0.0009 | 0.0011 | 0 | 0.9601 | 0.007 | 0.247 | 0.069 | 0.0291 |
| SW33 | 0.0039 | 0.0271 | 0.0147 | 0.0001 | 0.0019 | 0.0002 | 1.194 | 0.0512 | 0.539 | 0.084 | 0.022 |
| SW34 | 0.0039 | 0.0439 | 0.0005 | 0.0003 | 0 | 0 | 0.0091 | 0.0078 | 0.279 | 0.118 | 0.0412 |
| SW35 | 0.0033 | 0.0848 | 0.0039 | 0.0016 | 0 | 0 | 0.004 | 0.0016 | 0.546 | 0.044 | 0.0291 |
| SW37 | 0.0053 | 0.1469 | 0.0032 | 0.0026 | 0.0002 | 0 | 0.0078 | 0.0007 | 0.538 | 0.005 | 0.0238 |
| SW38 | 0.004 | 0.0243 | 0.0144 | 0 | 0 | 0 | 0.0282 | 0.0007 | 0.329 | 0.055 | 0.018 |
| SW39 | 0.0005 | 0.0754 | 0.0008 | 0.0015 | 0 | 0 | 0.0062 | 0.0004 | 0.414 | 0.116 | 0.0186 |
| SW40 | 0.0048 | 0.0476 | 0.0054 | 0 | 0 | 0 | 0.0052 | 0.0004 | 0.376 | 0.085 | 0.0055 |
| SW41 | 0.0035 | 0.0465 | 0.0038 | 0 | 0.0001 | 0 | 0.057 | 0.0005 | 0.307 | 0.054 | 0.0252 |
| SW42 | 0.0037 | 0.0339 | 0.0028 | 0.0002 | 0.0001 | 0 | 0.0874 | 0.0033 | 0.244 | 0.024 | 0.0265 |
| Minimum | 0.0001 | 0.0161 | 0 | 0 | 0 | 0 | 0.0002 | 0.0002 | 0.125 | 0.005 | 0.0001 |
| Average | 0.0037 | 0.0690 | 0.0043 | 0.0014 | 0.0008 | 0.0004 | 0.1279 | 0.0285 | 0.4000 | 0.1114 | 0.0307 |
| maximum | 0.0178 | 0.547 | 0.0161 | 0.0072 | 0.0251 | 0.0119 | 1.194 | 0.376 | 0.614 | 0.332 | 0.306 |

Table 19. Treated wastewater (mg/l).

| Sample ID | Arsenic (As) | Barium (Ba) | Cadmium (Cd) | Cobalt (Co) | Chromium (Cr) | Copper (Cu) | Iron (Fe) | Manganese (Mn) | Nickel (Ni) | Lead (Pb) | Zinc (Zn) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| SW36 | 0.0016 | 0.0329 | 0.0044 | 0.001 | 0 | 0 | 0.0069 | 0.0032 | 0.69 | 0.028 | 0.0321 |

Table 20. Groundwater trace elements (mg/l).

| Sample ID | Arsenic (As) | Barium (Ba) | Cadmium (Cd) | Cobalt (Co) | Chromium (Cr) | Copper (Cu) | Iron (Fe) | Manganese (Mn) | Nickel (Ni) | Lead (Pb) | Zinc (Zn) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Z1 | 0.005 | 0.0398 | 0.0062 | 0.002 | 0.0006 | 0 | 0.0021 | 0.0001 | 3.32 | 0.2107 | 0.0068 |
| Z2 | 0.0047 | 0.0732 | 0 | 0.0015 | 0 | 0 | 0.0018 | 0.0004 | 2.401 | 0.0275 | 0.0408 |
| Z3 | 0.0078 | 0.037 | 0 | 0 | 0 | 0 | 0 | 0.0003 | 3.131 | 0.312 | 0.0003 |
| Z4 | 0.0022 | 0.0531 | 0 | 0.002 | 0.0001 | 0 | 0.0069 | 0.0536 | 2.624 | 0.1443 | 0.0051 |
| Z5 | 0.0027 | 0.0146 | 0.0036 | 0.0008 | 0.0007 | 0 | 0.0011 | 0.0001 | 3.162 | 0.1103 | 0.0279 |
| Z6 | 0.0002 | 0.0218 | 0.0008 | 0 | 0 | 0 | 0 | 0.0003 | 0.808 | 0.0013 | 0.0048 |
| Z7 | 0.0033 | 0.2152 | 0.0014 | 0.0014 | 0 | 0 | 0.0103 | 0.0063 | 2.982 | 0.3222 | 0.0007 |
| Z8 | 0.0003 | 0.0498 | 0.0037 | 0.0007 | 0.0003 | 0 | 0.2038 | 0.3355 | 0.526 | 0.0597 | 0.0097 |
| Z9 | 0.0033 | 0.057 | 0.0066 | 0.0024 | 0.0001 | 0 | 0.0002 | 0.0183 | 2.802 | 0.0767 | 0.0311 |
| Z10 | 0.0007 | 0.0755 | 0.0243 | 0 | 0.0002 | 0 | 0 | 0.0688 | 1.196 | 0.4851 | 0.0228 |
| Z11 | 0.0021 | 0.2981 | 0 | 0.0007 | 0 | 0 | 0 | 0.0453 | 1.975 | 0.178 | 0.0036 |
| Z12 | 0.0018 | 0.0619 | 0 | 0.0009 | 0 | 0 | 0 | 0.0018 | 2.038 | 0.0187 | 0.0036 |
| Z13 | 0.0007 | 0.0796 | 0 | 0.0001 | 0 | 0 | 0.002 | 0.005 | 1.356 | 0.0585 | 0.0166 |
| Z14 | 0.0013 | 0.1326 | 0 | 0.003 | 0.0006 | 0.0335 | 0 | 0.0954 | 1.448 | 0.1443 | 0.2621 |
| Z15 | 0.0051 | 0.2166 | 0 | 0 | 0.0001 | 0.0024 | 0 | 0.0121 | 1.182 | 0.4401 | 0.0721 |
| minimum | 0.0002 | 0.0146 | 0 | 0 | 0 | 0 | 0 | 0.0001 | 0.526 | 0.0013 | 0.0003 |
| average | 0.0027 | 0.0951 | 0.0031 | 0.001 | 0.0002 | 0.0024 | 0.0152 | 0.0429 | 2.063 | 0.1726 | 0.0339 |
| maximum | 0.0078 | 0.2981 | 0.0243 | 0.003 | 0.0007 | 0.0335 | 0.2038 | 0.3355 | 3.32 | 0.4851 | 0.2621 |

# 5.0 DISCUSSIONS

## 5.1 Physico-chemical Parameters

The surface water is slightly alkaline to alkaline, fresh, soft to very hard whereas the treated waste water is slightly alkaline, fresh and hard. Groundwater is slightly acidic to alkaline, fresh to saline and soft to very hard.

With the exception of the three samples in the groundwater, both groundwater and surface water of the study area show a high pH value as compared to the treated wastewater. High pH values could be associated with pollution emanated from the different activities of the society in the villages that are drained by the both surface water and groundwater of the catchment. A discharge of used water by the users that contains detergents and soap-based products can cause the water to become too basic.

This high pH can causes a bitter taste, water pipes and water-using appliances become encrusted with deposits, and it also depresses the effectiveness of the disinfection of chlorine, thereby causing the need for additional chlorine when pH is high.

Among the examined water samples, the highest value of both EC and TDS were measured in the groundwater of the catchment. 67 and 60 percent of the total groundwater samples have an EC of greater than 1000 µS/cm and a TDS greater than 1000 ppm, respectively. The minimum EC and TDS values are measured in boreholes Z1 and Z5, which are located in the downstream side far from the river influences. The highest value of EC and TDS was measured in borehole Z10, which is located in Mochudi village. In general boreholes close to the river bank of Notwane River (Z4, Z7, Z11, Z14 and Z15) and upstream side (Oodi and Mochudi villages) have high values of dissolved solids and electric conductivity values. These might be due to human activities associated with those major villages that have high number of population found in this part of the catchment.

This significant high value of EC and TDS of the groundwater as compared to the surface water and treated water suggesting that the groundwater is not only an infiltration of the local precipitation and treated water rather have an additional source (regional ) besides to that of surface water and the treated water. Uncontrolled sewage, pit latrines, fertilizer, pesticides application in farms and water rock interaction could also be contributed to the rise of these chemical parameters in the groundwater.

Both the surface water and treated water alkalinity is a typical of fresh water alkalinity, which is in the range of 20 to 200 mg/l of $CaCO_3$. Generally both waters are not poorly buffered, and are not also very susceptible to changes in pH from natural and human-caused sources.

With the exception of one sample, the alkalinity of the groundwater ranges from 43.31 to 474.06 mg/l of $CaCO_3$ with mean value of 206.36 mg/l of $CaCO_3$. This range of alkalinity is high as compared to the surface water and treated water. Groundwater sample Z7 has the highest alkalinity of 1208.53 mg/l. The borehole from which sample Z7 was collected is located close to the river bank of Notwane River in the middle of study area (after the river has collected surface water from Bokaa, Pilane and Mochudi villages). The wastewater from the houses of the major villages or household wastes could be source of this high alkalinity in the groundwater. The wastewater from our houses contains carbonate and bicarbonate from the cleaning agents and food residue that we put down our drains. The cause to high alkalinity of the groundwater could also be the cause to this high hardness in the groundwater.

### 5.2 Water type

Fifteen water types are recognized in the surface water of the studied area. Among them the dominants are Na-$HCO_3$-Cl, Na-Mg-$HCO_3$-Cl and Ca-Mg-Na-HCO3. The treated wastewater is Na-Mg-HCO3-Cl type. Thirteen types of groundwater are identified in the study area. Among those water types the dominant ones are Mg-Ca-Na-Cl and Mg-Cl-HCO3. In all the dominant water types of surface water and groundwater including treated wastewater the chemical analyses indicated the existence of Cl as major constituent in these water, and all these are found in the upstream side and middle of the catchment, suggesting a possible link with the anthropogenic activities associated with development activities in the upstream side of the catchment.

### 5.3 Major Ions

In all the waters, surface water, treated wastewater and groundwater based on the mean values of the chemical parameters, the cations were in the order of abundance as $Na^+ > Ca^{2+} > Mg^{2+} > K^+ > Li^+$. Based on the mean values of the chemical parameters in the surface water the anions were in the order of abundance as $HCO_3^- > Cl^- > SO_4^{2-} > NO_3^- > PO_4^{3-} > F^- > CO_3^{2-}$, in the treated water $HCO_3^- > Cl^- > NO_3^- > SO_4^{2-} > PO_4^{3-} > F^- > CO_3^{2-}$ while in the ground water the anions reveal order of abundance as $Cl^- > HCO_3^- > SO_4^{2-} > NO_3^- > CO_3^{2-} > F^- > PO_4^{3-}$.

In the treated wastewater, the concentration of the major cations with the exception of Li have a concentration greater than the concentration in the surface water , whereas in the groundwater the concentrations of all the major cations are greater than the concentrations of the major cations in both the surface and treated waste water.

In the treated wastewater, the concentration of the analyzed major anions with the exception of fluorine and carbonate, have a concentrations greater than surface water whereas in the groundwater, the concentration of all the analyzed major anions are greater than the concentrations of both the surface and treated wastewater, with the exception of carbonate and phosphate.

In the groundwater, the measured concentration of $Cl^-$ (1322.5 mg/l) and $NO_3^-$ (60.67 mg/l) is much greater than the measured concentrations of these ions both in the surface and treated wastewater whereas the measured concentration of $PO_4^{3-}$ in the groundwater is significantly less than the measured concentration of $PO_4^{3-}$ in both surface water and treated wastewater. The highest measured concentration of $PO_4^{3-}$ (9.53 mg/l) is in the treated wastewater. Uncontrolled human wastes or sewage are the possible sources of $Cl^-$ and $NO_3^-$ ions in the groundwater. The presence of high concentration of phosphate ion in the treated wastewater and absence of more or less corresponding concentration in both the surface water and groundwater implies that the treated water is not the source for pollution to both surface and groundwater in the catchment.

In the analysed groundwater of the catchment the concentrations of all the analyzed major cations and anions (with the exception of carbonate and phosphate) are greater than the concentrations of the analyzed major cations and anions in both the surface water and treated waste water suggesting that the overall chemistry of the groundwater is not only controlled by the chemistry of the original precipitation and the chemistry of the treated wastewater rather by the water-rock interaction processes while the groundwater transmitted and stored in the different rock formations of the catchment .

Supporting this idea the Gibbs diagram below (Figure 20) shows the controlling mechanism of groundwater quality is rock weathering dominance. Fourteen samples out of fifteen are within the rock weathering dominance, while one sample collected in borehole Z7 indicated evaporation dominance.

In addition to that Figure 21 (dominant cation vs dominant anions) also shows that silicate weathering is the major process that control the rock-water interaction processes in the catchment. Most of the boreholes are drilled in the igneous rocks formation found in the upstream side of the catchment.

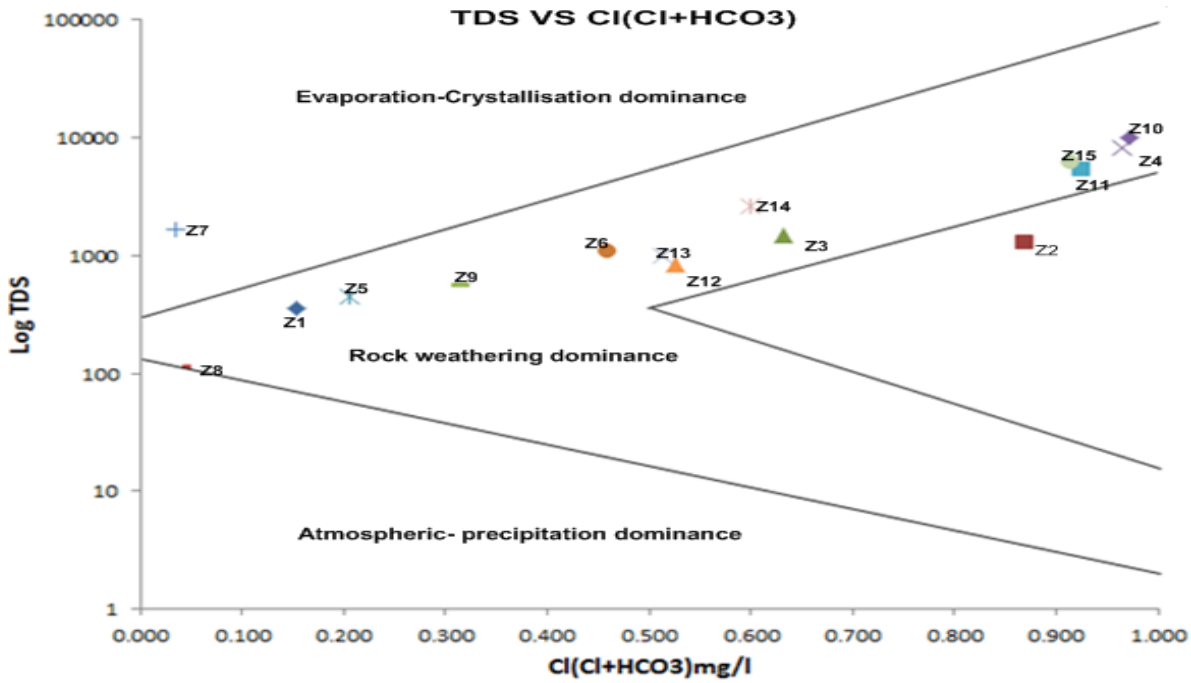


Figure 20. Gibbs diagram for groundwater.

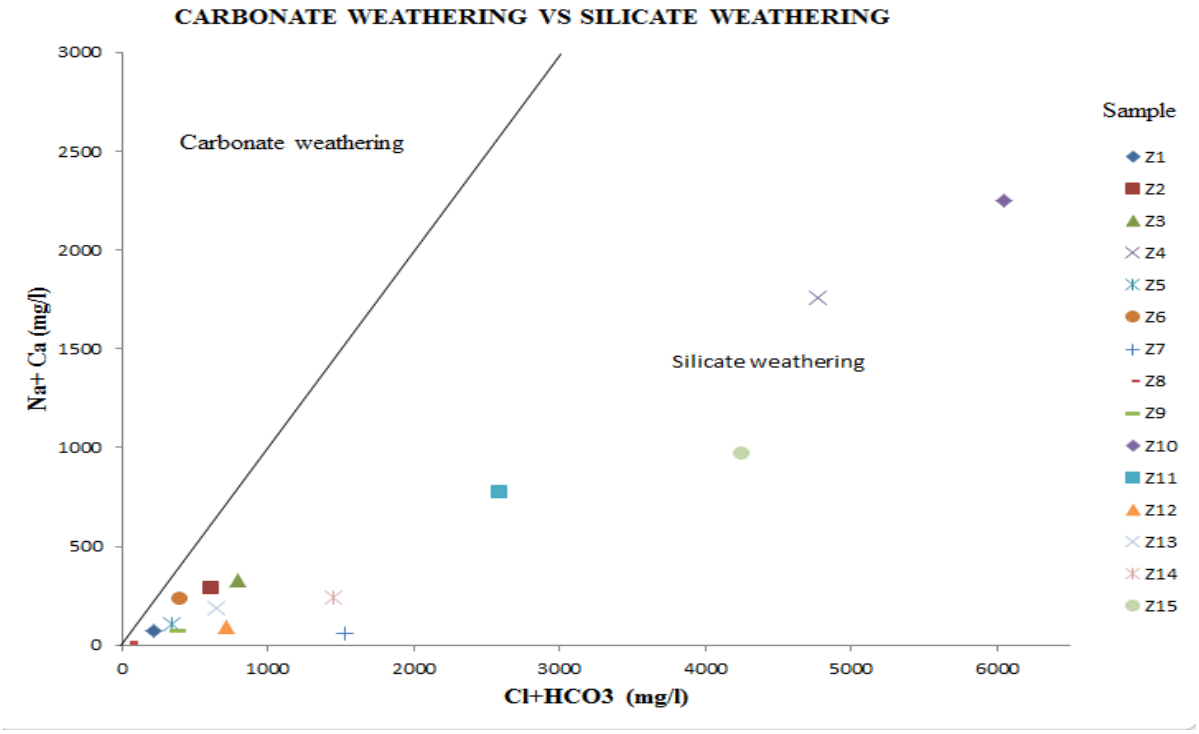


Figure 21. Groundwater carbonates weathering vs silicate weathering.

### 5.4 Trace elements

All the analyzed trace elements in the treated wastewater, with the exception of cadmium and cobalt, have a concentration less than the concentration in the groundwater of the catchment. In the treated wastewater, with the exception of Ni and Zn, all the remaining analyzed trace elements have a concentration less than concentration in the surface water. Therefore in the treated wastewater the concentration of zinc is insignificant to be a pollutant. However the concentration of Ni is not avoidable to be a pollutant toward the surface water and groundwater of the catchment: though it is not the only source. The different mineralogical compositions of the rocks of the studied area have also their own contribution.

# 6.0 WATER SUITABILITY

The suitability of the waters of the studied area for drinking purpose was evaluated using both standards set by WHO (WHO, 2004) and Botswana Bureau of Standard (BOBS second edition 2009) (Table 21).

Surface water, treated wastewater and groundwater satisfy the pH drinking water standard of both WHO and Botswana Bureau of Standards.

Both surface water and treated wastewater suit the EC and TDS standard of both WHO and Botswana Bureau of Standards whereas groundwater is highly above the recommended limits of standards set by both WHO and Botswana Bureau of Standards.

All analysed cations for surface water and treated wastewater satisfy the standard of both WHO and Botswana Bureau of Standards whereas in the groundwater the cations are highly above the recommended limits of the standards set by both WHO and Botswana Bureau of Standards with the exception of lithium and potassium.

The tested anions for surface water and treated wastewater satisfy the standard of both WHO and Botswana Bureau of Standards whereas in the groundwater the concentration of Cl and $NO_3$ were above the standards set by both WHO and Botswana Bureau of Standards. According to the U.S. Council of Environmental Quality (2006), "Cancer risk among people drinking chlorinated water is 93% higher than among those whose water does not contain chlorine." Also $NO_3$ above recommended standard cause abnormal production of red blood cells which also cause cancer.

In the analysed trace elements for all the waters, almost all samples met the trace element standards set by both WHO and Botswana Bureau of Standards with the exception of nickel and lead in surface water, treated wastewater and groundwater. According to the world health organisation guidelines (2004) for drinking-water consumption of water with nickel above recommended level can cause stomach aches skin irritation and reproductive and developmental toxicity. Furthermore accumulation or intake of excess lead can cause anaemia central nervous system problems and it can also affect kidney and immune system.

Table 21. BOBS and WHO drinking water standard.

| **STANDARDS (lifetime consumption)** | **WHO (2004)** | **BOBS(2009)** |
|---|---|---|
| pH | 6.5-9.5 | 5.5-9.5 |
| TDS | - | 1000mg/l |
| EC | 1500 µs/cm | 1500 µs/cm |
| **Parameter** | **mg/l** | **mg/l** |
| Calcium(ca) | - | 150 |
| Potassium(k) | - | 50 |
| Lithium(li) | - | - |
| Magnesium(mg) | - | 70 |
| Sodium(Na) | 200 | 200 |
| Arsenic (As) | 0.01 | 0.01 |
| Barium (Ba) | 0.7 | - |
| Cadmium( Cd) | 0.003 | 0.003 |
| Cobalt (Co) | - | 0.5 |
| Chromium(Cr) | 0.05 | 0.05 |
| Copper (Cu) | 2 | 2 |
| Iron (Fe) | - | 0.3 |
| Manganese (Mn) | 0.04 | 0.1 |
| Nickel (Ni) | 0.02 | 0.07 |
| Lead (Pb) | 0.01 | 0.01 |
| Zinc (Zn) | - | 5.0 |
| Chloride (Cl) | 250 | 200 |
| Sulphate ($SO_4$) | 500 | 250 |
| Nitrate ($NO_3$) | 50 | 50 |
| Flourine (F) | 1.5 | 1.0 |

# 7.0 CONCLUSION AND RECOMMENDATION

## 7.1 Conclusions

In all the water, surface water, treated wastewater and groundwater, the dominant cations and anions are sodium, calcium, bicarbonate and chlorine. In all the waters the dominant cation is $Na^+$. In all the waters, surface water, treated wastewater and groundwater, based on the mean values of the chemical parameters, the cations were in the order of abundance as $Na^+ > Ca^{2+} > Mg^{2+} > K^+ > Li^+$. In both the surface water and treated wastewater the dominant anion is $HCO3^-$ whereas in groundwater is $Cl^-$. Based on the mean values of the chemical parameters, in the surface water the anions were in the order of abundance as $HCO_3^- > Cl^- > SO_4^{2-} > NO_3^- > PO_4^{3-} > F^- > CO_3^{2-}$, in the treated water $HCO_3^- > Cl^- > NO_3^- > SO_4^{2-} > PO_4^{3-} > F^- > CO_3^{2-}$ while in the groundwater the anions reveal order of abundance as $Cl^- > HCO_3^- > SO_4^{2-} > NO_3^- > CO_3^{2-} > F^- > PO_4^{3-}$.

Among the analyzed trace elements, the dominant in all the water, surface water, treated waste water and groundwater is nickel. Based on the mean values of the chemical parameters, the order of abundance of trace elements in the surface water was Ni > Fe > Pb > Ba > Zn > Mn > Cd > As > Co > Cr > Cu, in the treated wastewater Ni > Ba > Zn > Pb > Fe > Cd > Mn > As > Co > Cr and Cu having equal concentration (0 mg/l) while in the groundwater the analyzed trace element reveal order of abundance as Ni > Pb > Ba > Mn > Zn > Fe > Cd > As > Cu > Co > Cr.

The overall chemical analyses of the water chemistry revealed that the hydrochemistry of the groundwater in the study area is not only controlled by the chemistry of the original precipitation, chemistry of surface water and chemistry of treated wastewater but also dominantly by the water-rock interaction processes while the groundwater transmitted and stored in the different rock formations of the catchment and anthropogenic activities in the area.

The analysed cations for surface water and treated wastewater satisfy the standard of both WHO and Botswana Bureau of Standards whereas in the groundwater the cations are highly above the recommended limits of the standards set by both WHO and Botswana Bureau of Standards with the exception of potassium.

The tested anions for surface water and treated wastewater satisfy the standard of both WHO and Botswana Bureau of Standards whereas in the groundwater the concentration of Cl and $NO_3$ were above the standards set by both WHO and Botswana Bureau of Standards.

In the analysed trace elements for all the waters, almost all samples met the trace element standards set by both WHO and Botswana Bureau of Standards with the exception of nickel and lead in surface water, treated wastewater and groundwater.

Generally, on the basis of the overall chemical analyses of the water chemistry, the study revealed that treated wastewater quality does not have any significant harm to both surface and groundwater quality, therefore it can be used as a source of recharge to the aquifers in the catchment.

### 7.2 Recommendations

Currently the treated wastewater is serving a limited purpose in the country and the major portion is flowing out of the country. With regard to the finding of this research the treated wastewater quality does not have significant harm to the quality of both surface water and groundwater. Therefore, rather than letting the treated wastewater to flow out of the country, the researcher recommends a construction of a better storage/pond than the one which is available now that can store this water and make available for various uses in the country.

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# 8.0 APPENDIX

**8.1** Summary of dominant elements concentrations as water flows from Gaborone dam (upstream) to downstream (Mmakgopong).

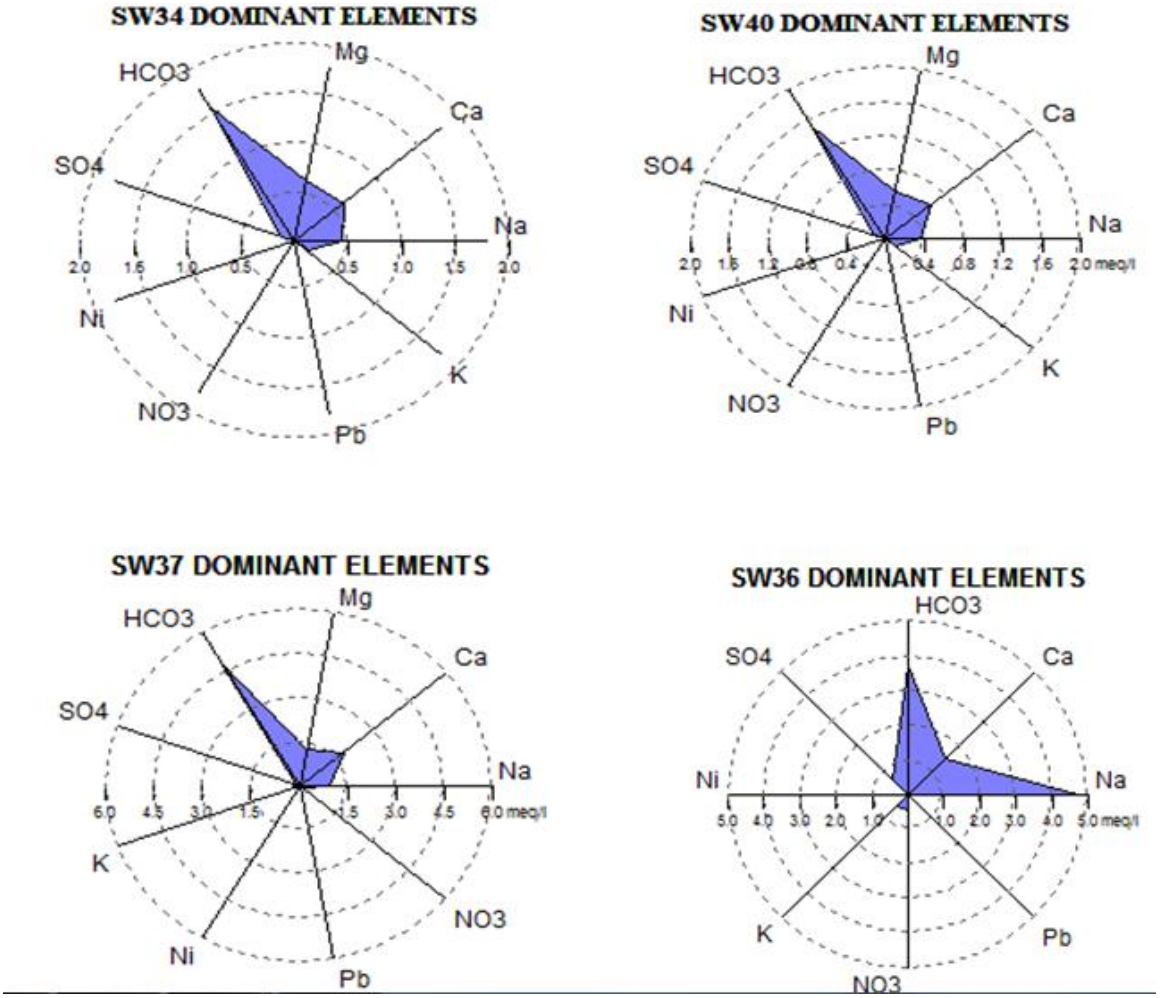


Figure 22: Summary of dominant elements concentrations upstream (SW34, SW40**,** SW37) including treated wastewater (SW36).

| **Sample ID** | **DISCRIPTION** |
|---|---|
| SW34 | Reference sample collected from Gaborone Dam (upstream of study area) before mixing with waters from Gaborone city |
| SW40 | Surface water in Notwane river after mixing with water from part of city |
| SW37 | From part of Gaborone city before it combines with Notwane river |
| Sw36 | After Final sewage treatment stage before it meets the Notwane river |

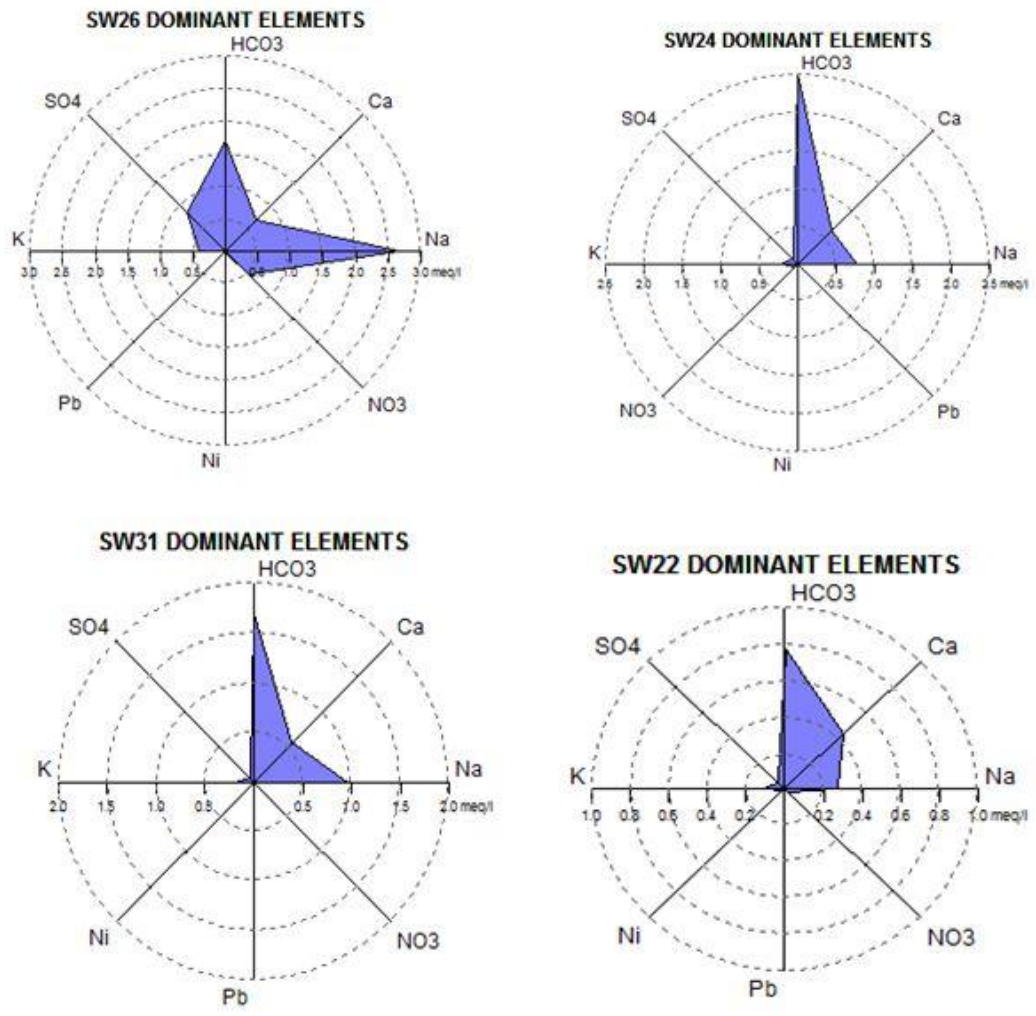


Figure 23: Summary of dominant elements concentration in middle of study area (SW26, SW24, SW31 and SW22)

| **Sample ID** | **DISCRIPTION** |
|---|---|
| SW26 | Collected in notwane river after it combines with treated water+ surface water from Gaborone + surface water from Segoditshane river |
| SW24 | Surface water from a small stream in Matebele before it joins Notwane river. |
| SW31 | Reference sample from Bokaa Dam before it combines with Notwane river |
| SW22 | Collected in Metsimotlhabe river after Bokaa village and before it combines with Notwane River. |

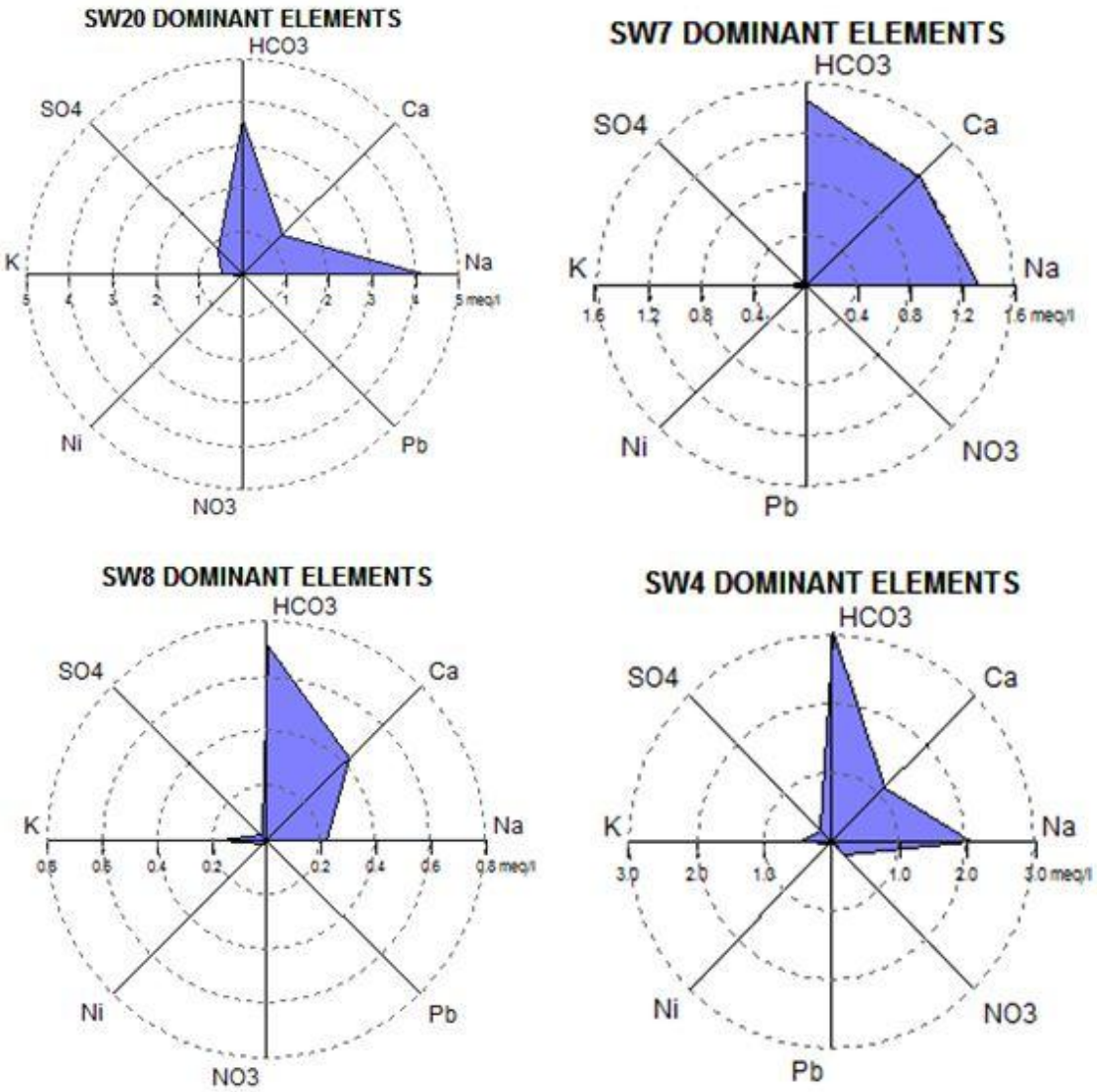


Figure 24: Summary of dominant elements in middle and downstream of study area (SW20, SW7, SW8 and SW4)

| **Sample ID** | **DISCRIPTION** |
|---|---|
| SW20 | Sample collected after Metsimotlhabe river combines with Notwane river |
| SW7 | Sample collected from Tlhagale River before it joins Notwane river. |
| SW8 | Sample collected after Tlhgale River combines with Notwane river |
| SW4 | Sample collected further downstream in Notwane River |

## 8.2 Secondary data

Table 22: Previous borehole water analysis in the study area

| Time analysed | 1986 | 2016 |
|---|---|---|
| borehole ID | Z6 | Z6 |
| EC ms/cm | 426 | 1509 |
| PH | 7.64 | 7.53 |
| TDS ppm | 258 | 1080 |
| Ca mg/l | 24 | 89.52 |
| Mg mg/l | 16 | 44.82 |
| Na mg/l | 41 | 142.5 |
| K mg/l | 2.1 | 9.7 |
| Cl mg/l | 13 | 180.88 |
| SO4 mg/l | 9.5 | 424.46 |
| F mg/l | 0.31 | 0.5 |
| NO3 | 0.49 | 32.06 |

### 8.3 Water level analysis

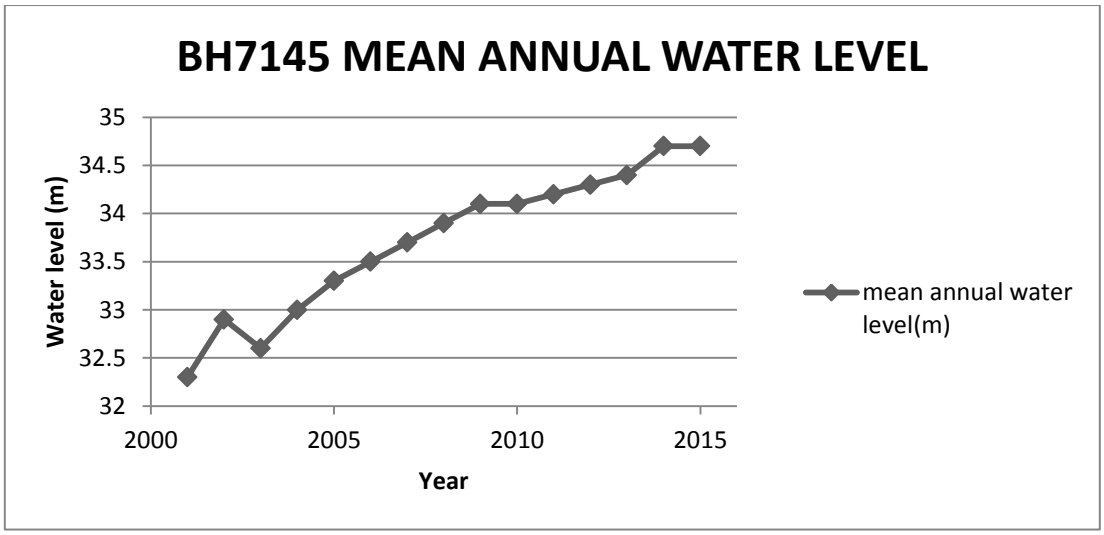


Figure 25: Water level graph in a monitoring borehole BH7145

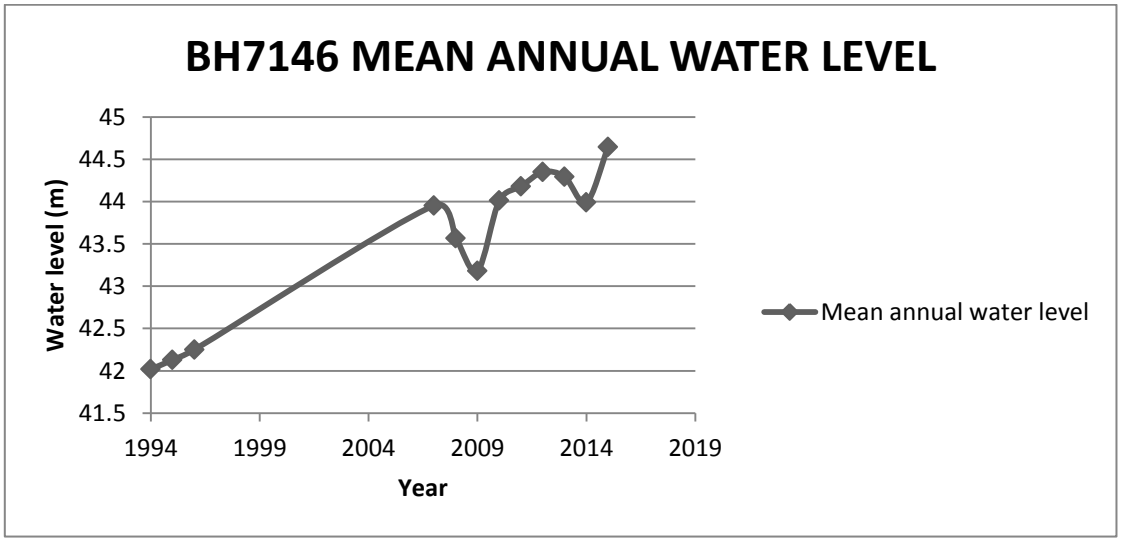


Figure 26: Water level graph in a monitoring borehole BH7146

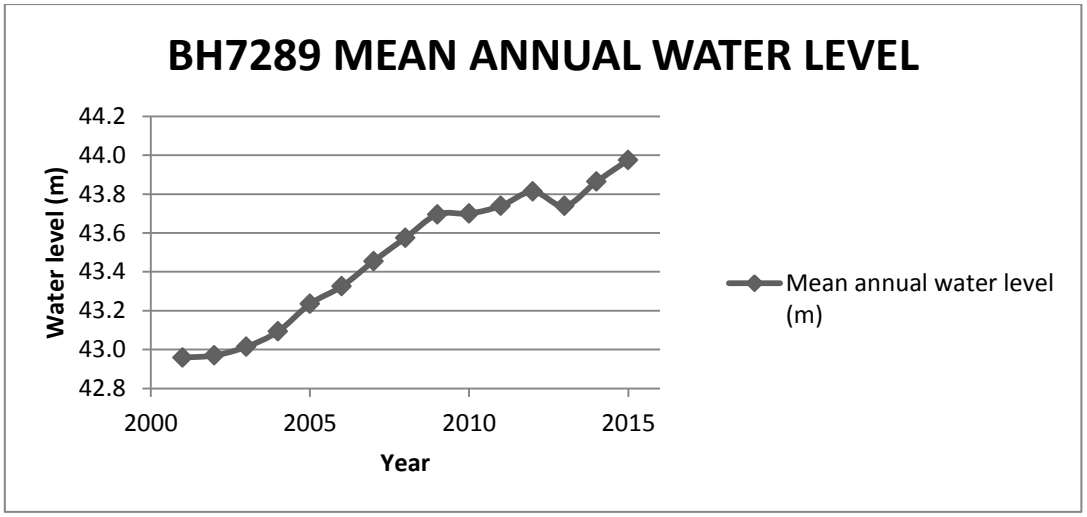


Figure 27: Water level graph in a monitoring borehole BH7289

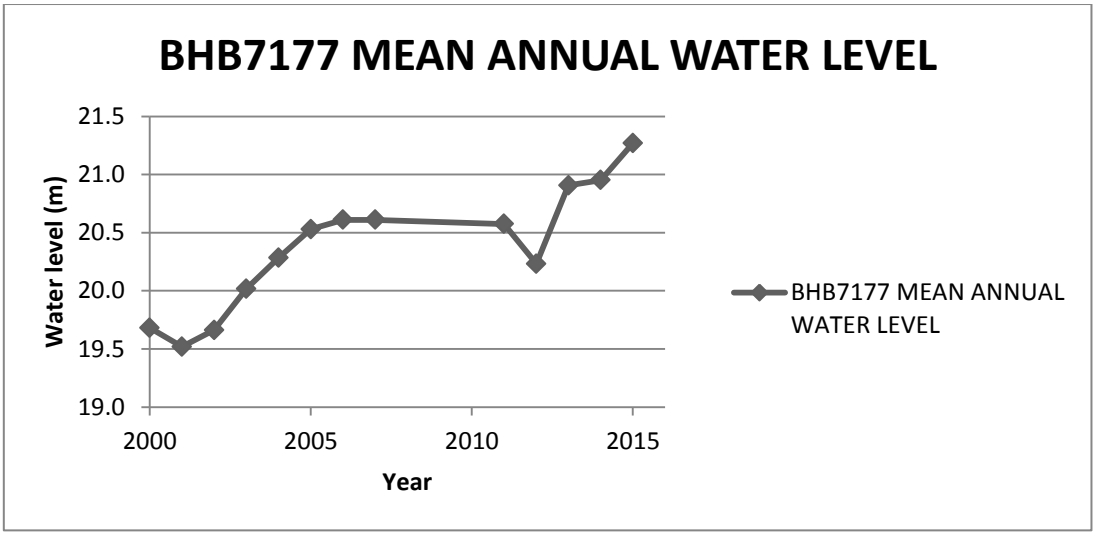


Figure 28: Water level graph in a monitoring borehole BH7177