Impacts of Treated Wastewater on the Surface Water and Groundwater Quality: A Case Study in North East Gaborone, Botswana

Tshepo K[1] iD
Tafesse NT[2] ✉ iD
Chaoka RT[3] iD
Alemaw BF[4] iD
Laletsang K[5] iD

[1,2,3,4,5]*Department of Geology, University of Botswana, Gaborone, Botswana*
[2]*Email:* *tafesse24603@yahoo.com* *Tel:* +267 75908000

(✉ *Corresponding Author*)

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 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 wastewater 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). 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 range from slightly alkaline to very hard whereas the treated wastewater is slightly alkaline to hard and groundwater is slightly acidic 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 groundwater 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.

Contents

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

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% [1]. According to Botswana Central Statistics Office [2] 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 Botswana Central Statistics Office [2] 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 Bureau of Standards [3] 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 24.61^0S and longitude 25.96^0E in Glen Valley (Gaborone North-east), downstream of Gaborone Dam. The first phase of a treatment works has a capacity of 40,000 m³/day and operating at an average of 20 000 m³/day. The second face of the plant has a capacity of 50 000 m³/day and has not started operating which totals to 90000 m³/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, 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.

The impacts of treated wastewater in Gaborone are generally based on wastewater 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 and Ramolemana [4] 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. 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 [5]. 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 pollutions sources.

1.2. Objectives

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

The following were 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.

1.3. Description of the Study Area

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.In general the area is undulating with slopes from south-east (upstream) to north-east (downstream). The Notwane River drains north - east into the Limpopo River and has tributaries Metsimotlhaba, Thagale and Monametsanarivers.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.The study is area 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

Figure 1 and 2 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.
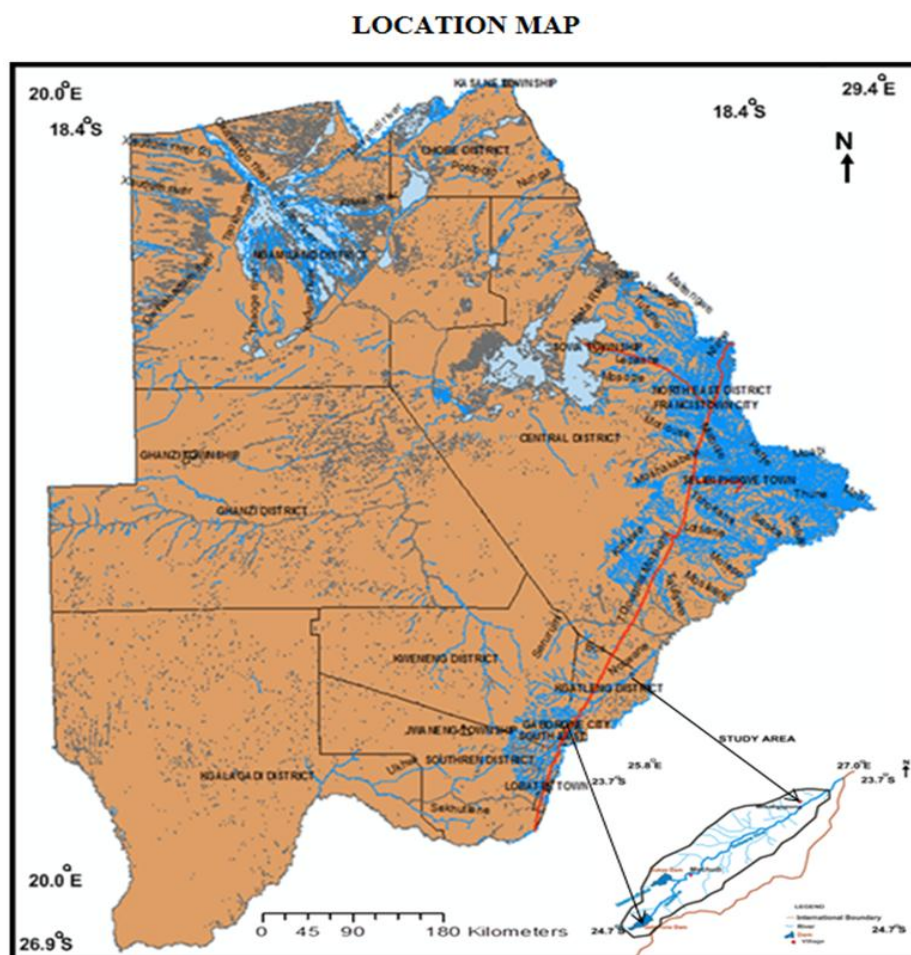
LOCATION MAP

Figure-1.Location map of study area.

Source: Tshepo K., M.Sc. Thesis, University of Botswana, Gaborone, Botswana, 2017.
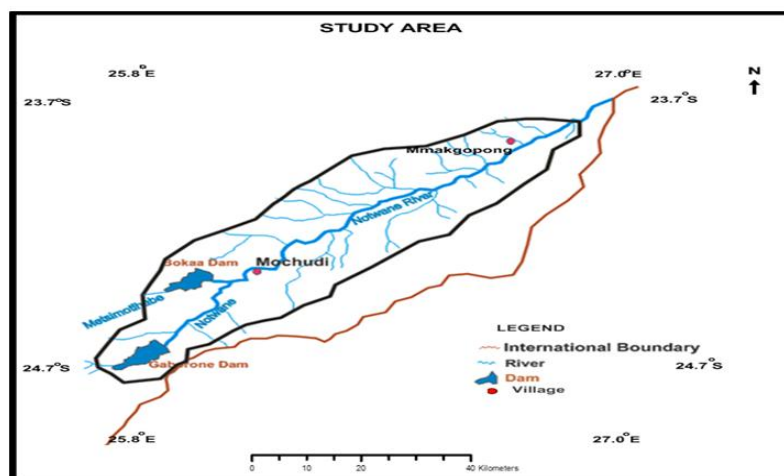
Figure-2. Study area in Notwane catchment.
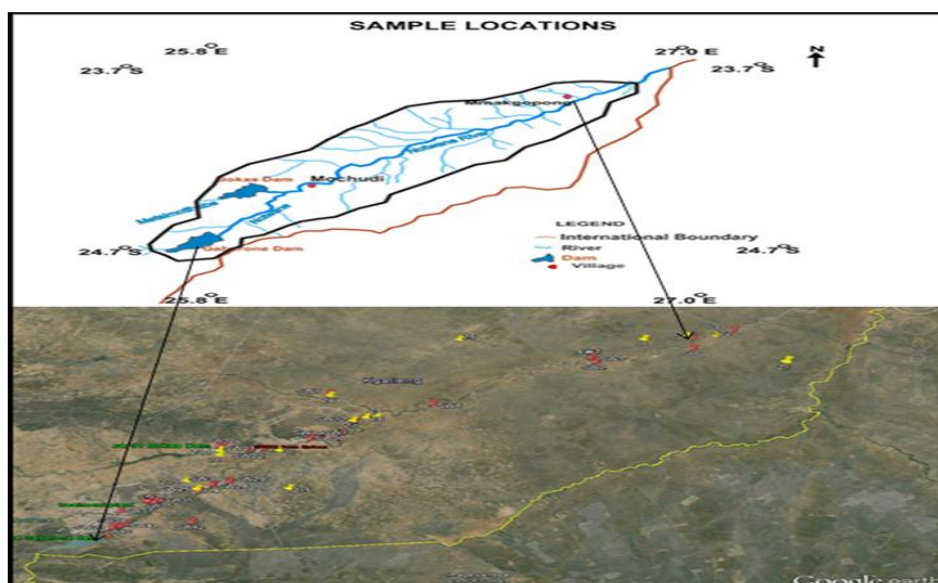**Source:** Tshepo K., M.Sc. Thesis, University of Botswana, Gaborone, Botswana, 2017.

Figure-3. Sample location
Source: Tshepo K., M.Sc. Thesis, University of Botswana, Gaborone, Botswana, 2017.

2. Methodology

2.1. 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 3). 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.

2.2. 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 3), 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 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 3).

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

2.3. 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 analysis.

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 [6] and the Botswana Bureau of Standard [7].

3. Results and Discussions
3.1. Physico-Chemical Parameters
The surface water is slightly alkaline to alkaline, fresh, and 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.
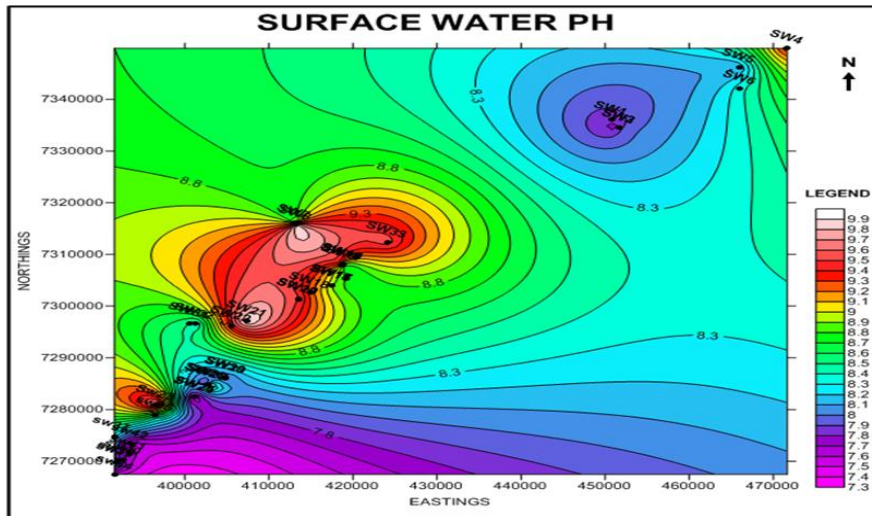

Figure-4. Surface water pH
Source: Tshepo K., M.Sc. Thesis, University of Botswana, Gaborone, Botswana, 2017.
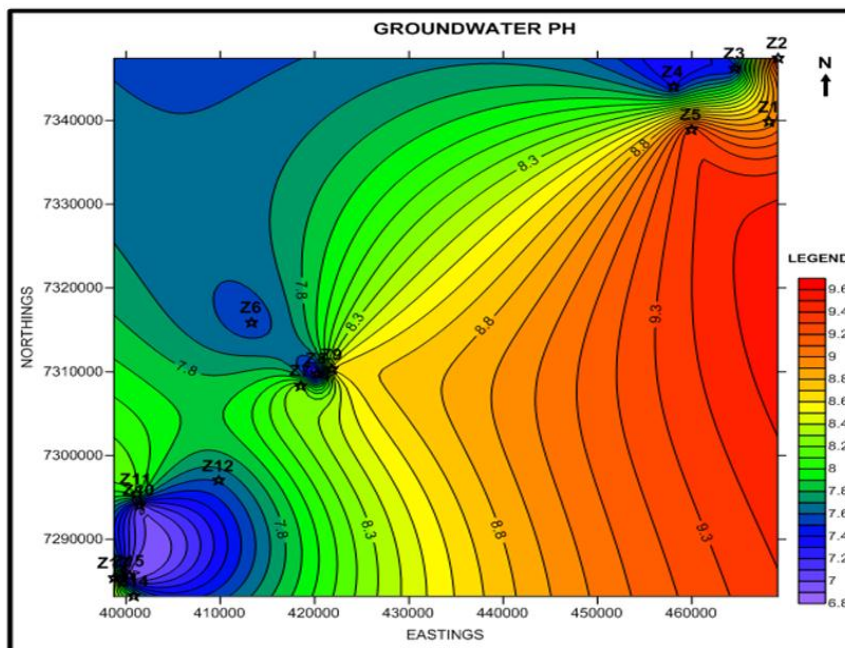

Figure-5. Groundwater pH.
Source: Tshepo K., M.Sc. Thesis, University of Botswana, Gaborone, Botswana, 2017.

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.

The table below shows the general water classification scale based on TDS [8].

Table-1. Groundwater classification

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

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.

3.2. 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-$HCO3$ (Table 1).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.

3.3. 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 groundwater the anions reveal order of abundance as $Cl^- > HCO_3^- > SO_4^{2-} > NO_3^- > CO_3^{2-} > F^- > PO_4^{3-}$.

The Figures 6 and 7 below show the piper diagram for surface water and treated wastewater and groundwater, respectively. Fig. 6 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. 7 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. 6). 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. 7).

Table-2. Water types

	Surface water		Groundwater		Treated wastewater	
Sample ID	water type	Sample ID	Water type		Sample ID	water type
SW1	Na-Mg-CO3	Z1	Mg-Na-HCO3		SW36	Na-Mg-HCO3-Cl
SW2	Na-HCO3-CO3	Z2	Na-Mg-Cl			
SW3	Na-HCO3	Z3	Na-Cl-HCO3			
SW4	Mg-Na-Ca-HCO3	Z4	Mg-Na-Ca-Cl			
SW5	Ca-Na-HCO3	Z5	Na-Mg-HCO3-Cl			
SW6	Na-HCO3	Z6	Na-Ca-Mg-SO4-Cl-HCO3			
SW7	Mg-Na-Ca-HCO3	Z7	Mg-HCO3			
SW8	Ca-Mg-Na-HCO3	Z8	Ca-Mg-HCO3-NO3			
SW9	Mg-Na-Ca-HCO3	Z9	Mg-Na-HCO3-Cl			
SW10	Na-Mg-HCO3-Cl	Z10	Mg-Ca-Na-Cl			
SW11	Na-Mg-Ca-HCO3	Z11	Mg-Ca-Na-Cl			
SW12	Mg-Ca-Na-HCO3	Z12	Mg-Cl-HCO3			
SW13	Na-HCO3-Cl	Z13	Na-Mg-Cl-HCO3			
SW14	Na-Mg-HCO3-Cl	Z14	Mg-Cl-HCO3			
SW15	Na-HCO3-Cl	Z15	Mg-Ca-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					

Source: Tshepo K., M.Sc. Thesis, University of Botswana, Gaborone, Botswana, 2017.
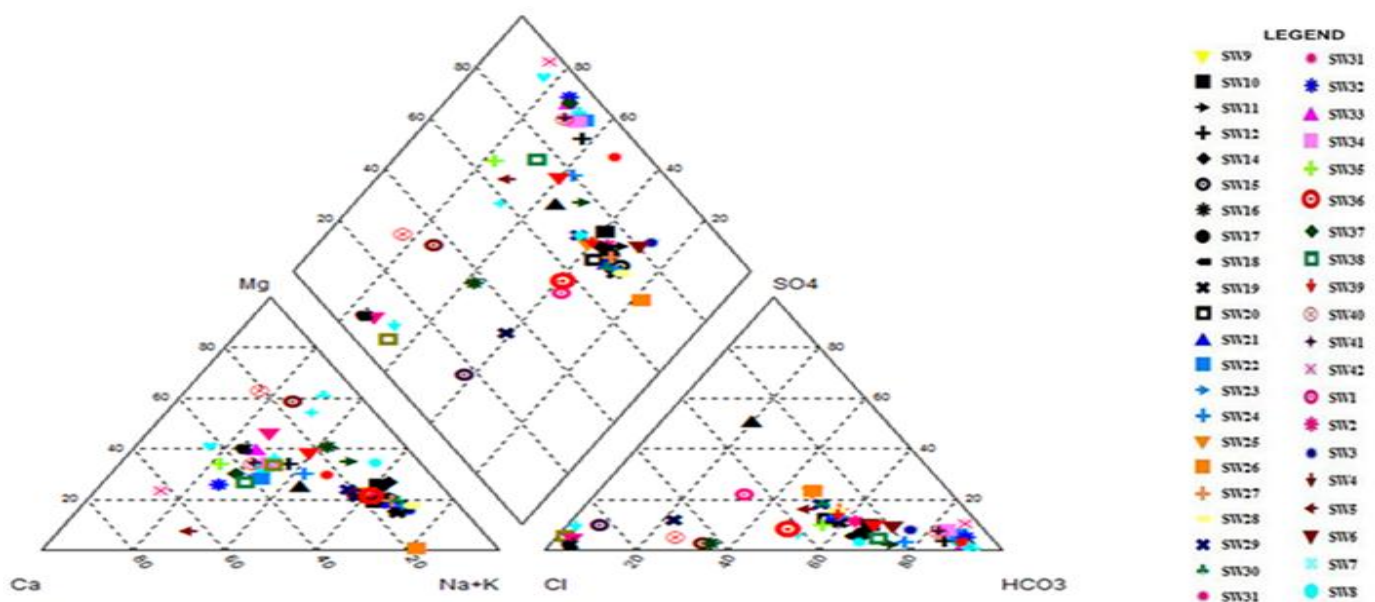

Figure-6. Surface water piper plot

Source: Tshepo K., M.Sc. Thesis, University of Botswana, Gaborone, Botswana, 2017.
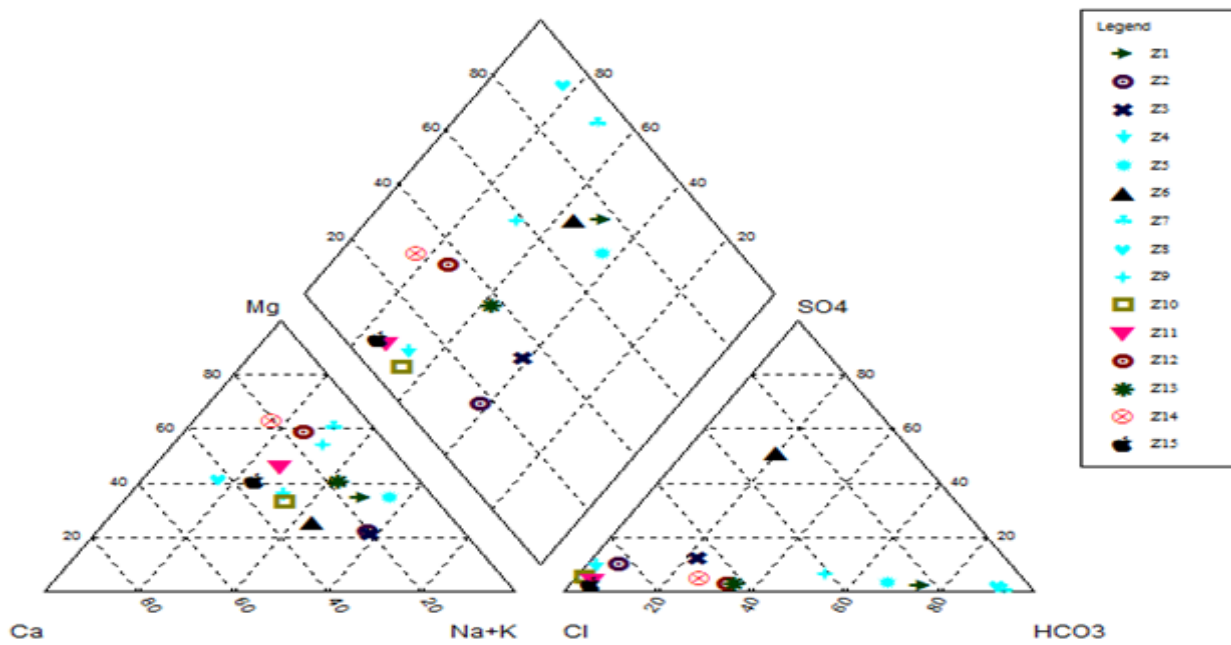
Figure-7. Groundwater piper plot

Source: Tshepo K., M.Sc. Thesis, University of Botswana, Gaborone, Botswana, 2017.

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 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 8) 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 9 (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.
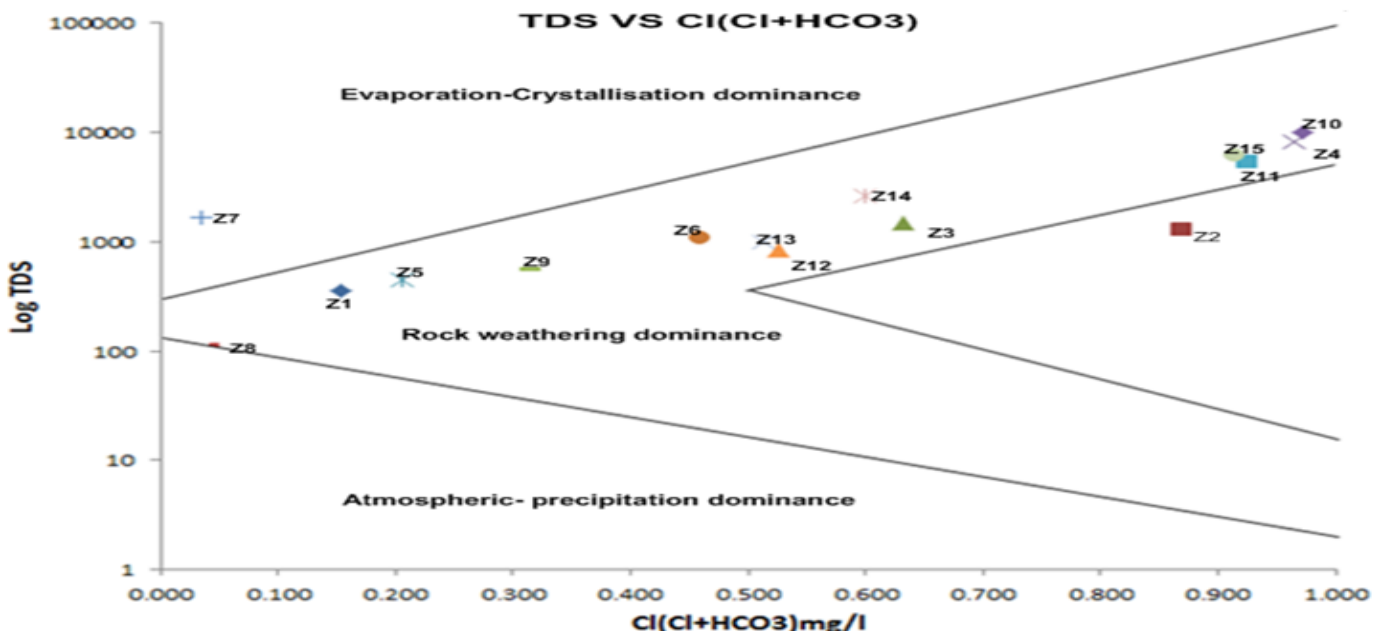

Figure-8. Gibbs diagram for groundwater.

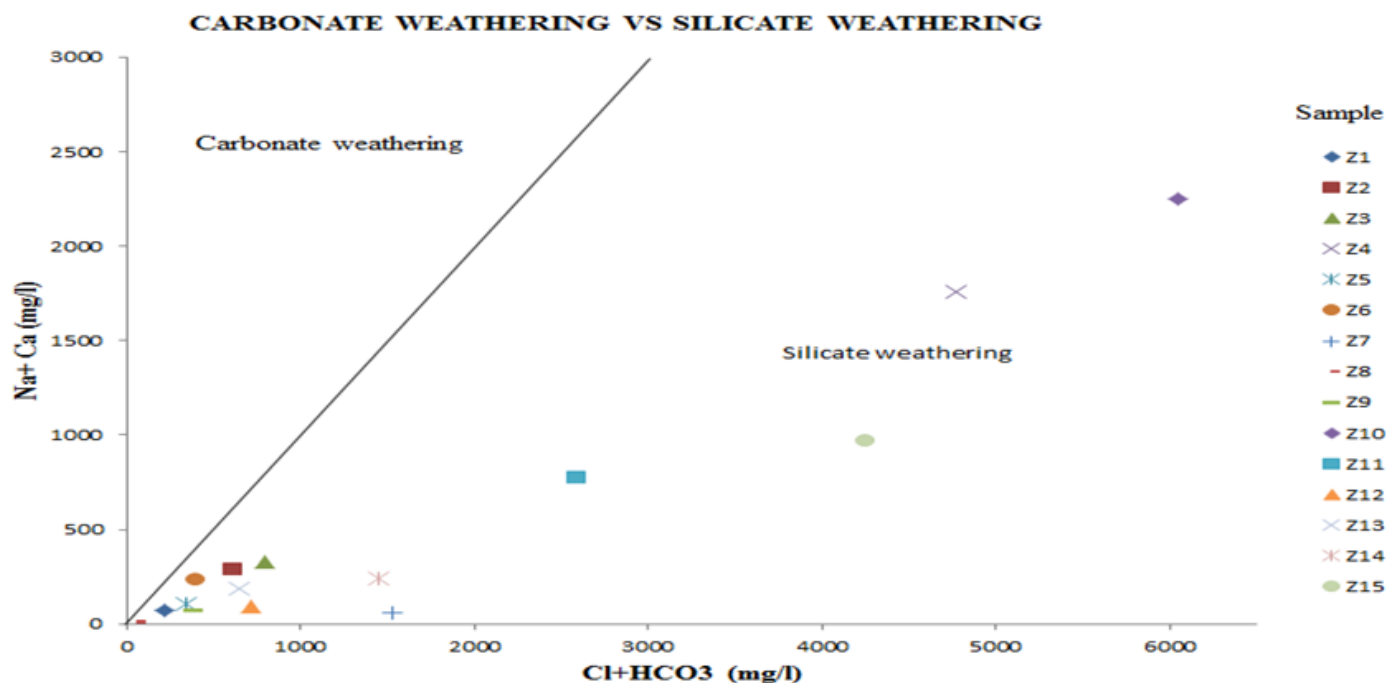**Source:** Tshepo K., M.Sc. Thesis, University of Botswana, Gaborone, Botswana, 2017.

Figure-9. Groundwater carbonates weathering vs silicate weathering.
Source: Tshepo K., M.Sc. Thesis, University of Botswana, Gaborone, Botswana, 2017.

3.4. 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.

4. 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 HCO_3^- 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 wastewater 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 andBotswana Bureau of Standards. In the analysed trace elements for all the waters, almost all samples met the trace element standards set by both WHO andBotswana 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.

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