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Assessment of the impacts of groundwater pumpage on the future water supply sustainability in Zanzibar, Tanzania

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ASSESSMENT OF THE IMPACTS OF GROUNDWATER PUMPAGE ON THE FUTURE WATER SUPPLY SUSTAINABILITY IN ZANZIBAR, TANZANIA

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A Dissertation Submitted in Partial Fulfillment of the Requirements for the Degree of Master's in Hydrology and Water Resources Engineering of the Nelson Mandela African Institution of Science and Technology

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ABSTRACT

In the present study, a 42-year record of rainfall and temperature from Airport and a 43-year rainfall record from Kizimbani meteorological station were analyzed to understand how these climatic variables are affecting groundwater resources on the Island of Zanzibar, Tanzania. Water table fluctuation, abstraction volume and different Physico-chemical parameters such as chlorinity, nitrate, electrical conductivity and total dissolved solids were also studied. The balance between groundwater recharge and water abstraction rates and assess the impact of groundwater pumpage on water quality on the island of Zanzibar was estimated. Through the use of the water table fluctuation (WTF) method, this study estimated the local sustainable yield (SY) and integrated water balance (IWB) in Zanzibar. Rainfall records showed that Zanzibar Island receives a total mean annual rainfall of 1673 mm out of which 7% (equivalent to 1.79 x 10^6 m^3/y) recharges the groundwater. Temperature variations indicated an incremental trend accompanied by low rainfall. The average estimated local sustainable yield was 0.72% while the integrated water balance showed a deficit of 39%. Furthermore, the total groundwater abstraction rate in the studied area was 2.49 x 10^6 m^3/y, which is higher than the rate of recharge. This means that the groundwater resources are currently over-exploited and if immediate action is not taken, the groundwater aquifers may be subjected to pollution, collapse, and seawater intrusion. The effects of over-pumping are being manifested by the levels of EC, Cl^-, TDS, total hardness (TH) and nitrate that have shown an increasing trend with time. Due to the high variation of temperature, a controlled infiltration of harvested rainwater is suggested as a sustainable solution for salt intrusion as well the balance way of recharge and abstraction rate in Zanzibar and other islands.

DECLARATION

I, Zuleikha Pembe Ali, do hereby declare to the Senate of Nelson Mandela African Institution of Science and Technology that, this dissertation is my own original work and that it has neither been submitted nor being concurrently submitted for degree award in any other institution.

Zuleikha P. Ali (Candidate name)	**Date**

The above declaration is confirmed

Dr. Mwemezi J. Rwiza (Supervisor)	**Date**

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CERTIFICATION

The undersigned certifies that they have read and hereby recommend for acceptance by Nelson Mandela Institution of Science and Technology a dissertation titled "Assessment of the impact of groundwater pumpage on the future water supply sustainability in Zanzibar, Tanzania" in fulfillment of the requirements for the degree of Master's of Water Supply and Sanitation of the Nelson Mandela African Institution of Science and Technology.

____________________________________ ________________________

Dr. Mwemezi J. Rwiza (Supervisor) **Date**

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For the sake of Allah (S.W) who is the greater of whole learning and shrewdness invested to humankind and his Holy Prophet Muhammad who is perpetual, a way of direction and information for mankind.

First of all, I would like to thank my supervisors at Nelson Mandela Institution of Science and Technology Dr. Mwemezi Rwiza and Professor Alfred N. N. Muzuka (R.I.P) for their direction and valuable feedback all through my research. Their understanding, patient, and collaboration amid the whole research work will never be overlooked.

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Lastly, but most importantly, I would like to express my special gratitude to my family, my husband, Mr. Mohammed Zubeir Kombo, my daughter Kauthar and my brother-in-law Shaame Adam for their moral support during the period that I was absent from home to pursue my studies.

DEDICATION

To my lovely son, Maahir, my young brothers and sisters as well as my parents, Mrs. Fathiya and Mr. Pembe, for their prayers, care, guidance and support during my studies.

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LIST OF ABREVIBRATION AND SYMBOLS

AMS	Airport Meteorological Station
BH	Borehole
DO	Dissolved Oxygen
EC	Electrical Conductivity
GW	Groundwater
IWB	Integrated Water Balance
KMS	Kizimbani Meteorological Station
Max.	Maximum
Min.	Minimum
NM-AIST	The Nelson Mandela African Institution of Science and Technology
P	Population
Pr	Pumping Rate
R	Recharge
RGoZ	Revolutionary Government of Zanzibar
SY	Sustainable Yield
TDS	Total Dissolved Oxygen
TH	Total Hardness
Wd	Water Demand
WTF	Water Table Fluctuation Method
ZAWA	Zanzibar Water Authority

CHAPTER ONE

INTRODUCTION

1.1 Background of the problem

Water is a vital resource for human life as it supports agriculture, energy, health and domestic use (Loucks & Jia, 2012). But nearly 1.1 billion people have a shortage of clean and safe water for use, and often rely on unsafe ground or surface water supply systems (Peter-Varbanets *et al.*, 2009). In Africa, over 300 million people have no access to safe drinking water (MacDonald *et al.*, 2012). In Tanzania, water provision to the majority of the population is still a challenge. Over 89% of Tanzanians collect water from public places such as wells, streams, and watersheds which is sometimes not safe for human consumption (Taylor *et al.*, 2013). Groundwater is an important source of freshwater globally (Mirzavand & Ghazavi, 2015). In Tanzania groundwater is a key component of potable water supply (Taylor *et al.*, 2013). However, Freshwater management is difficult, particularly because of variations in the hydrologic cycle associated with global and regional climatic changes.

On Zanzibar (Unguja) Island, local communities depend solely on the limited groundwater supply for their freshwater needs, and the groundwater table is gradually being contaminated by salt intrusion (Mato, 2015). High salt contamination is a result of increasing local water shortages because of over-pumping of groundwater (Malesu *et al.*, 2007). Furthermore, the coastal population is increasing at an unprecedented rate, with a growing tourist industry where more hotels catering for the tourists use large amounts of water in showers, sanitation, and swimming pools, all of which increase water demand (RGoZ, 2015). Water shortage in Unguja is also caused by depletion of underground water sources from uncontrolled economic activities such as poor intensive farming systems, deforestation in catchment areas, increased tourism, and poor drainage systems, all of which interfere with the hydrological recharge.

The main sources of groundwater are shallow hand-dug wells, boreholes and cave wells. The dug wells and boreholes are the main water sources, where water is abstracted from 15 to 20 m below the ground (Mohamed *et al.*, 2016). In the Urban West area, there are presently 11 production boreholes with a total water pumping rate of 18 300 m^3/day, and many are close to the Indian Ocean coast (Mato, 2015). In this study, only seven boreholes were selected.

Halcrow (1994) reported that the amount of groundwater is directly proportional to the amount of rainfall received. The challenge for Zanzibar is how to maintain the abstraction level below the recharge amount (ZAWA, 2008). According to ZAWA (2008) the present estimated mean abstraction rate in Zanzibar is about 71 million m^3 per annum, with the upper limit being 339 million m^3 per annum (Table 1).

Table 1: Groundwater recharge and abstraction rates on Zanzibar Island

Parameter (million m^3)	Unguja	Pemba	Total
Average annual Rainfall	2445	1525	3970
Estimated groundwater recharge	565	121	686
Acceptable aquifer yield	293	46	339
Estimated actual abstraction	60	11	71
Estimated ZAWA abstraction	23	10	33

Source: ZAWA (2008)

Thus, understanding groundwater pumpage and rate of recharge are essential for sustainable water supply in Zanzibar because of the gradual impacts of groundwater pumpage on water chemistry. However, such information is scarce. This study investigated how groundwater pumpage is likely to impact the future water supply on Zanzibar (Unguja) Island.

1.2 Statement of the problem

There is a water supply deficit on Zanzibar Island because the island depends solely on groundwater supply systems namely shallow wells, boreholes, and cave wells (RGoZ, 2015). These groundwater sources are based on coastal aquifers. When subjected to over-pumping due to high water demand, seawater intrusion increases (Mato, 2015). Seawater intrusion increases the salinity of the local groundwater sources, rendering water from the affected sources unfit for domestic as well as other uses in the tourism and agriculture sectors (Hansson, 2010). Consequently, seawater intrusion problems make most of the affected groundwater sources to be abandoned. This is especially so during the dry season when there is peak water demand, leaving the island residents with huge water deficits. In Bwejuu village, for instance, water from some wells is too saline to be used for cooking and drinking purposes, and the sources have been abandoned (Hansson, 2010).

Besides high salinity due to seawater intrusion, groundwater sources in Zanzibar face seasonal imbalances between the source supply and demand. These imbalances often occur during dry season when the hydrological groundwater recharge is low relative to the increased abstraction rates. Thus, the present study examined how abstraction has affected water quality and how the abstraction and population increase are likely to affect water supply in Zanzibar.

1.3 Rationale of the study

Zanzibar (and esp. Unguja) Island is one of the most vulnerable regions to water scarcity and salinity in Tanzania (Mato, 2015). The island relies on groundwater sources that are hydraulically connected to the seawater systems, making it vulnerable to seawater intrusion and hydrological water imbalances. Seawater intrusion has resulted in increased groundwater salinity while hydrological imbalances have lowered the amount of groundwater supply.

As the water supply on Zanzibar island decreases, the demand for freshwater for domestic use, tourism and agriculture increases. The increasing water supply deficit in Zanzibar has often increased the island's vulnerability to waterborne diseases such as cholera, dysentery and other sanitation challenges. This study, therefore, sought to assess the hydrological groundwater imbalances (recharge and abstraction rates) and salinity in Zanzibar. This study is also based on the recommendation by Malesu *et al.* (2007) who recommended the assessment of groundwater recharge to get optimum abstraction for Zanzibar to avoid over-pumping.

1.4 Objectives

1.4.1 General objective

To assess the impacts of groundwater pumpage on the future of water supply sustainability in Zanzibar.

1.4.2 Specific objectives

(i) To estimate the balance between groundwater recharge and water abstraction rates.

(ii) To assess the impact of groundwater pumpage on water quality.

(iii) To project the future outlook of groundwater supply in Zanzibar.

1.5 Research questions

This research will be guided by the following research questions:

(i) What is the estimated balance between groundwater recharge and water abstraction rates?

(ii) To what extent is the groundwater in Zanzibar polluted due to pumpage?

(iii) What will be the future outlook of groundwater supply in Zanzibar?

1.6 Significance of the study

According to ZAWA (personal communication during field study), there is pressure on available water sources in Zanzibar. Some of the sources are already abandoned due to salt intrusion as a result of long-term pumpage. Therefore, a need has arisen to understand the impacts of groundwater pumpage in terms of long-term variabilities in groundwater quality and quantity. Effective management of groundwater calls for a more complete understanding of ground provenance, type and sources of its quality and suitability for use. Also planning land use and population control to ensure that groundwater is sufficiently protected from over-abstractions and pollution. The information obtained in the present study will give a clear picture of the current situation on water availability and water quality issues on the island.

1.7 Delineation of the study

This study covered the assessment of the impacts of groundwater pumpage on the future of water supply sustainability in Zanzibar, through understanding the balance between groundwater recharge and water abstraction rates in the required area, also how the groundwater polluted due to longterm pumpage and finally the future outlook of groundwater supply in Zanzibar which will helps the water management in Zanzibar to solve the water demand problems.

CHAPTER TWO

LITERATURE REVIEW

2.1 Groundwater quality and supply issues

It has been recorded that, globally, human consumption of freshwater far exceeds the currently available resources (Hinrichsen & Tacio, 2002; Jackson *et al.*, 2001) increasing water demands emanates from rapid urban development, poorly concentrated farming systems, deforestation in the catchment area, increased tourism and poor drainage systems, all of which interfere with the hydrological recharge systems (Changming *et al.*, 2001). Globally, extreme over-pumping of coastal aquifers is the most imperative anthropogenic reason for saltwater intrusion (Essink, 2001). In Zanzibar, a number of groundwater sources have recently been abandoned due to drying up and saline water intrusion. The information gathered from the Zanzibar Water Authority (ZAWA) suggests that between 2002 and 2005, about 15 pumped wells were abandoned due to salinity or depletion problems. Figure 1 illustrates issues related to groundwater quality and supply on the island of Zanzibar.

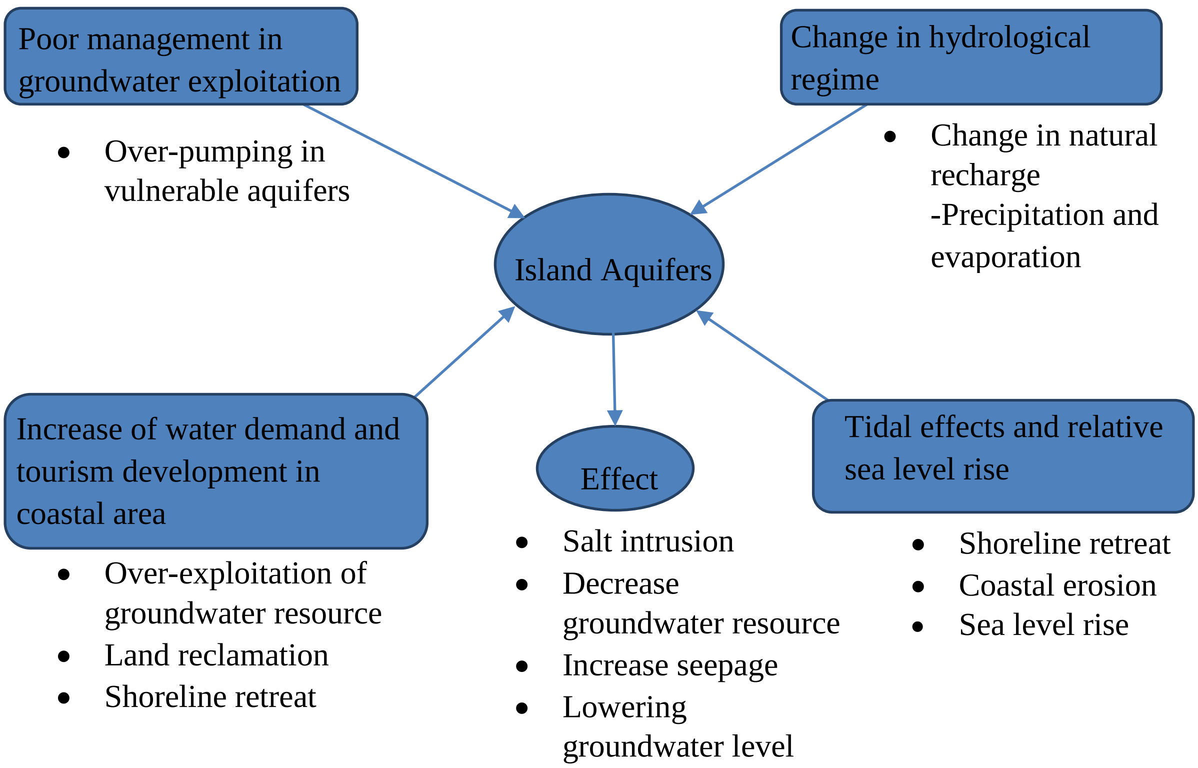

Figure 1: Schematic diagram indicating causes and effects of issues related to island groundwater quality and supply. (Essink, 2001)

2.2 The climate of Zanzibar

Climate change influences the hydrologic cycle through different pathways including shifts in precipitation and evapotranspiration (Elias *et al.*, 2016). Groundwater sources of Zanzibar are maintained by rain. The climate on the island is tropical, dominated by two distinct rainy seasons with long and short rains from March to May, and October to December, respectively. The total annual rainfall is 1600 mm and its distribution is indicated in Fig. 2, in which the long aka "*masika*" rains contribute heavily to the groundwater recharge (Haji, 2010).

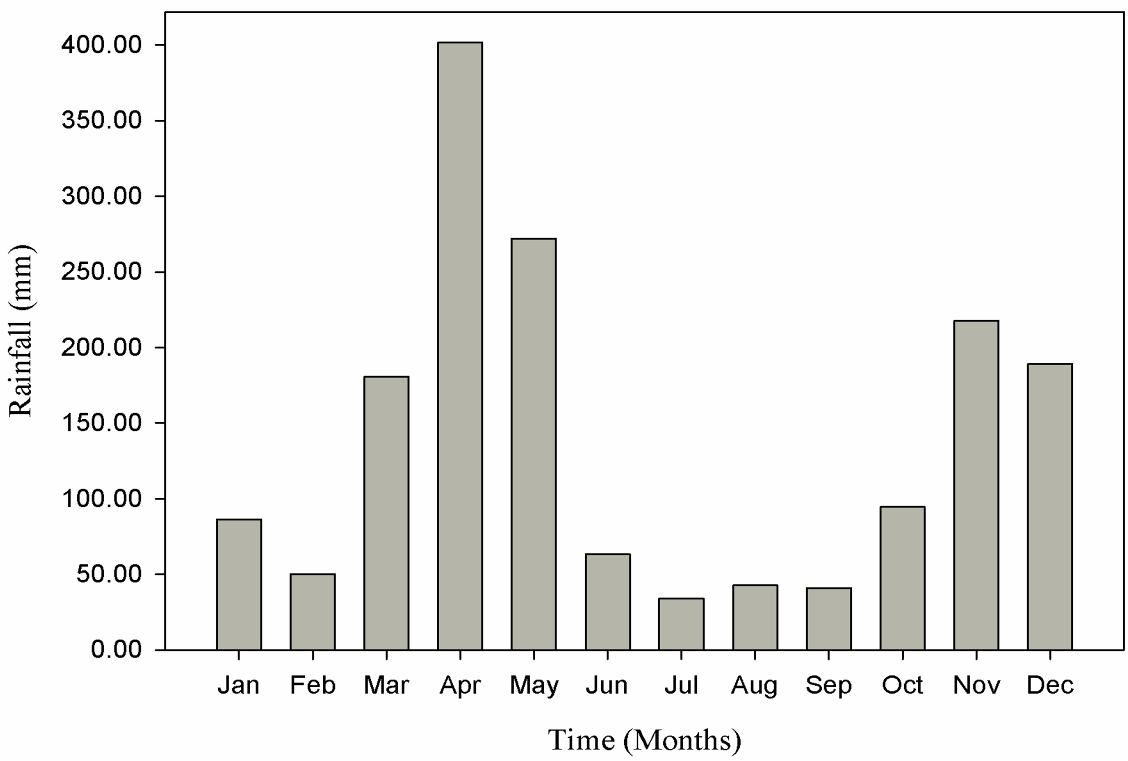

Figure 2: Average Monthly Rainfall in Unguja Island from 1991 to 2008. (Haji, 2010)

Currently, the mean annual day temperature is around 28 ^{0}C and the night temperature is about 19 ^{0}C. January to March is the hottest season with temperatures of 32 °C during the day and 23 °C at night (Hansson, 2010).

2.3 Climate change and water resources

Although Zanzibar is facing unprecedented water deficits coupled with the declining groundwater sources for its increasing population and the booming tourism industry, climate change and variability exacerbates the situation (RGoZ, 2015). Climate change-induced prolonged dry spells coupled with environmental deteriorations have significantly altered the hydrological cycles of the island, resulting in reduced quantity and quality of the groundwater systems (Kombo & Kanyama, 2015). Correlation between groundwater levels and precipitation over multiple timescales can assist in examining aquifer vulnerability to climate change and the indirect impact of pumping (Russo & Lall, 2017). The patterns of annual rainfall and runoff from the Zanzibar coastal basins have also reduced with some areas experiencing an extreme decline in precipitation amounts (Kombo & Kanyama, 2015). Surface runoff and groundwater flow in Mwanyanya and Mtopepo areas, for instance, have declined to more than half their original quantity (Kombo & Kanyama, 2015).

2.4 Groundwater recharge

In Zanzibar, long rains also known as "*masika*" rains, are the most important for groundwater recharge with the water table recovery being almost double of that during short rains i.e. "*vuli*" rains (Haji, 2010). During the long rains, that happens from March to May, the infiltration is rapid and drastically elevated water tables are registered almost immediately (Hansson, 2010). Table 2 shows the historical water recharge and other groundwater data of selected zones of the Zanzibar zone (Halcrow, 1994a).

Table 2: The estimated acceptable yields for various groundwater sources on Unguja Island

Water resource zones	Annual rainfall	Annual recharge	Groundwater flow to the sea	Annual acceptable yield
1. Kipange	122.6	23.99	9.49	14.5
2. Mwanakombo	251.8	68.53	35.04	33.49
3. Mchangani	289.9	72.40	38.33	34.07
4. Kitope	285.1	59.64	35.59	24.05
5. Zingwezingwe	134.2	19.13	11.68	7.45
6. Pangani	178.1	35.27	18.25	17.02
7. Kinyasini	391.9	130.00	38.33	91.67
8. Mwera	174.4	36.75	12.78	23.97
9. Bububu	616.6	143.00	82.13	60.88
TOTAL	2444.6	564.73	281.62	292.60

Halcrow (1994a)

Zanzibar experiences rise and fall in groundwater levels which interfere with the area water sources and supply systems. The long-term fluctuations in the groundwater table, extending for decades, are attributed to both natural and human causes (Healy & Cook, 2002). Natural causes include a decline in recharge systems, changes in hydrological cycles and climate change (Healy & Cook, 2002). Conversely, the anthropogenic causes of groundwater decline include irrigation, over-pumpage, deforestation and urbanization, among others (Healy & Cook, 2002).

2.4.1 Groundwater recharge estimation techniques

Groundwater recharge estimation is a key component in water resource management, mostly in areas with high rates of exploitation as it is for Zanzibar. There are different techniques for estimating groundwater recharge, and the most prominent ones include: (a) chemical tracer techniques such as chloride mass balance (CMB), (b) statistical approaches such as water table fluctuation (WTF), (c) Darcian approach, (d) water budget method and (e) numerical methods such as one or two-dimensional groundwater flow model (Healy & Scanlon, 2010;

Healy & Cook, 2002; Pan *et al.*, 2011). In the present study, water table fluctuation method was used due to the aquifer fluctuation characteristics of Zanzibar boreholes.

2.4.2 Water table fluctuation approach

This method is based on the assumption that the rise in groundwater levels in unconfined aquifers are due to recharge water reaching the water table (Healy & Cook, 2002; Scanlon *et al.*, 2002). This approach is mostly applied in regions with shallow water level fluctuation (Brears *et al.*, 2014). The general equation for WTF is represented in Equation (1) and described in detail by (Healy & Cook, 2002).

$$R = S_y \times \Delta H \qquad (1)$$

Where R is the recharge rate, S_y is aquifer specific yield and ΔH is the water level rise with respect to the recharge period. This technique has been used with the assumption that the specific yield (S_y) is constant throughout the underlying aquifer.

2.5 Conceptual review of sustainable yield (SY) based on WTF

Through the water table fluctuation method, it is important to consider the sustainable yield (SY) of the area. Sustainable yield is categorized into three groups such as average percentage (AP), least conservative (LC) and reasonably conservative (RC). The SY categories are estimated at 40%, 70% and 10% of total recharge volume respectively (Ponce, 2007b). In contrast, there is a growing number of hydrologists that consider SY on minute details of what happens to the groundwater system which puts into effect natural recharge as a key factor but further includes changes in recharge and discharge caused by pumping as equally very vital parameters to consider. Equation (2) is used to estimate the SY of an area, whereby:

$$SY = \Delta R - \Delta D \qquad (2)$$

Where ΔR = change in recharge caused by pumpage and ΔD= change in discharge caused by pumpage (Seward *et al.*, 2006).

2.6 Water quality in Zanzibar

Water, and especially safe and clean water, plays a significant role in our daily life; its cleanliness and safety are in terms of low organic and inorganic pollutants that are hazardous to human and environmental health (WHO, 2011). Water quality briefly explained, may be expressed in terms of the number of dissolved solids and biological pollutants (Tularam & Krishna, 2009). The geological setting of Zanzibar that is commonly very permeable soil sequences from the landscape level gives great infiltration capacities of expansive groundwater assets. However, the great invasion limits of the soil layers have serious disadvantages as such soil layers cannot provide protection against pollution. Pollution of groundwater is one of the real worries for human wellbeing in Africa and beyond (Elisante & Muzuka, 2017). In Zanzibar, groundwater is abstracted by the use of deep and shallow boreholes. The boreholes and groundwater are generally not protected from pollutant intrusion. This is the reason why these sources have been found to contain high levels of nitrate, sulphate and trace elements (Mohamed *et al.*, 2014). Moreover, from the present study, the data indicate a high amount of chloride (Cl) in water samples collected at Mbweni borehole. It is, therefore, necessary that the authorities in Zanzibar launch campaigns to protect groundwater sources.

2.7 Water pumpage in Zanzibar

The pumping out of groundwater is considered sustainable if the system can reach a new equilibrium in which no more groundwater is expelled from storage and water levels stabilize through the system (Bredehoeft & Alley, 2014). Water pumped from the groundwater system causes the water table to lower and alters the direction of groundwater movement (Sophocleous, 2002). For this study, groundwater abstraction data were based on the yield values from in-use wells. It is important to note, however, that many of the ZAWA-operated wells were not working due to water quality problems rendered by long term pumpage. Thus, seven boreholes were studied namely Kianga, Chunga, Kaburikikombe, Mbweni, Mwembemchomeke, Welezo and Kwarara. These boreholes were drilled at the year of 1961, 1974, 1996, 1983, 2002, 2004 and 2006 respectively.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study area description

The island of Zanzibar off the Dar Es Salaam coast in Tanzania is a world-renown tourist hotspot (Sharpley & Ussi, 2014). This study was conducted on the island of Zanzibar (also known as Unguja), located in the Indian Ocean, about 35 km off the Dar Es Salaam coast, Tanzania, at latitude 4°50' and 6°30' South and longitude 39°10' and 39°50' East. The island covers 86 km and 39 km in length and width, respectively with an area of 1658 km^2 (Siex, 2011). The island aquifers are found to be unconfined and interactive all over the island, underlain mainly with lower Miocene rocks consisting of deltaic sandstones related with marls and minor reef limestones (Sikat, 2011). The local population on the island is estimated at 896 761 according to the 2012 census. The main sources of income include fishing, agriculture, tourism and seaweed farming (Trowbridge *et al.*, 2006). On the island, seven (7) Urban West zones were randomly selected for the study, and these include Kianga, Chunga, Kaburikikombe, Mbweni, Mwembe mchomeke, Welezo and Kwarara (Fig. 3). Groundwater samples were taken from boreholes located in the above-mentioned zones.

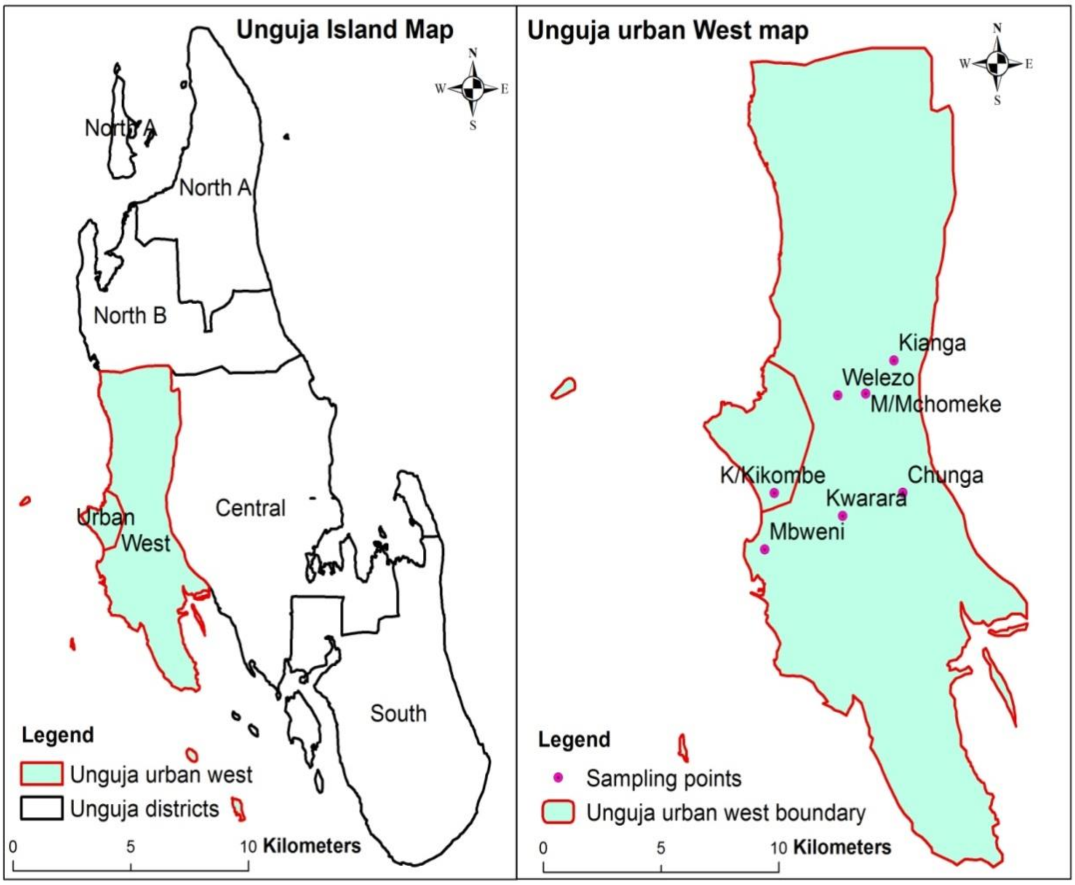

Figure 3: A map of Zanzibar (Unguja) Island (left) showing locations of the study sites (right)

3.2 Data collection

The data collected were climatic, water abstraction rates, water quality and borehole water levels. The climatic data were observed from two different Zanzibar meteorological stations at Zanzibar Airport and Kizimbani. Collected weather data observed at Zanzibar Airport station were temperature and rainfall whereas only rainfall data were obtained from the Kizimbani station. The rest of the data were obtained, with permission, from Zanzibar Water Authority (ZAWA), the office responsible for water supply and sanitation on the island.

3.3 Catchment area estimation

The catchment area was calculated/delineated from the georeferencedshapefile in ArcGIS version 10.1. The total catchment area is 227.5 km^2; the calculated area was used to, then, calculate recharge volume in m^3 by multiplying the depth value (m) with the area (m^2).

3.4 Groundwater sampling and analyses

Groundwater samples were collected from seven (7) constructed boreholes in the Urban West region of the island (Fig. 1). Sampling bottles were washed thrice in the laboratory before being rinsed using sampled water in the field. Before taking a sample, water was pumped for about 10 min, this ensured that the collected samples truly represented the groundwater and not the stagnant water that resides in the boreholes (Kura *et al.*, 2013). The samples were collected and stored in a clean and airtight 250.0 mL HDPE bottles and acidified using 0.5 mL HNO_3 to maintain a pH below 2.0 and were carried and stored at a temperature of 4.0^{0}C for analysis of major cations. Physico-chemical water quality parameters such as temperature, pH, electrical conductivity (EC), dissolved oxygen (DO), salinity and total dissolved solids (TDS) were measured on-site using multiparameter water analysis kit (ScichemTechSCT-THER-PEN-6). Groundwater TH was measured in the laboratory at the Nelson Mandela African Institution of Science and Technology (NM-AIST), Arusha, Tanzania.

3.4.1 Measurement of cationic and anionic concentrations

The following water quality parameters were measured in the laboratory at NM-AIST: Major cations (Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}) and anions (CO_3^{2-}, HCO_3^-, Cl^-, NO_3^-, and SO_4^{2-}). The major anions were immediately analyzed by SulfaVer.4, cadmium reduction, argentometric titration and titrimetric method respectively while TH and major cations were analyzed by EDTA Titrimetric and Flame Emission Photometry respectively.

3.5 Data analysis

Climatic data such as temperature and rainfall were statistically and graphically analyzed by two-time scales such as monthly and annual entire series by using SigmaPlot Version 11. The average abstracted rate was computed by using Microsoft Excel Version 2010. The groundwater recharge values were computed using the WTF method from the general Equation (1). This approach is mostly applied in the region with a shallow water table fluctuation (Brears & Post, 2014). Moreover, this technique has been used with the assumption that the specific yield (S_y) is constant throughout the underlying aquifer. The S_y values used were from the pumping test result from the study sites. The recharge rate was computed by using MS Excel Version 2010. In this study, S_y was not calculated but it based on pumping test results from the study area. The S_y values used for recharge rate estimations were 0.0035, 0.0037, 0.0170, 0.0120, 0.0120, 0.0010 and 0.0110 for Kianga, Chunga, Kaburikikombe, Mwembemchomeke, Welezo, Mbweni and Kwarara respectively. Fluctuations in groundwater level data were plotted alongside rainfall data to determine the validity of water level raise compared to precipitation.

It is also important to consider the effective sustainable yield (SY) of the area. The SY method is categorized into three groups such as average percentage (AP), least conservative (LC) and reasonably conservative (RC). The three SY percentages are estimated at 40%, 70% and 10% of total recharge volume, respectively (Ponce, 2007a). In contrast, there is a growing number of hydrologists that consider SY on minute details of what happens to groundwater systems which put into effect the natural recharge as a key factor but further includes changes in recharge and discharge caused by pumping as equally vital parameters to consider. Values of SY are calculated using the general Equation (2) as mentioned above.

The influence of groundwater pumpage on water chemistry against pumping age was analyzed by a scatter plot through SigmaPlot Version 11. Modeling for the projection of future outlook of groundwater supply in Zanzibar was calculated by applying a regression equation in GenStat Version 15 by considering key parameters such as pumping rate, recharge rate, population size and water demand due to population growth.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Climatic data

4.1.1 Rainfall

Climate change influences the hydrologic cycle through different pathways incorporating shifts in precipitation and evapotranspiration (Elias *et al.*, 2016). Groundwater resources of Zanzibar are maintained by rainfall events. This study applied rainfall data from two stations: (1) Zanzibar Airport station rainfall data were from 1975 to 2016 – a 42-y period and (2) Kizimbani rainfall data were from 1970 to 2012 – a 43-y period. As can be seen from the monthly and annual timescale plots (Figs. 4 and 5), the trends on monthly analysis were not significant on both stations. Annual rainfall plots, however, showed a slightly decreasing trend for both stations. Through computation, it was found that rainfall at the Airport and Kizimbani stations has been decreasing at a mean rate of 11.1 and 9.8 mm/y respectively. Although these annual rainfall decline rates may seem small, when taken over longer climatic periods, they are indeed significant. The decline in annual rainfall will, over longer times, affect groundwater recharge on the island.

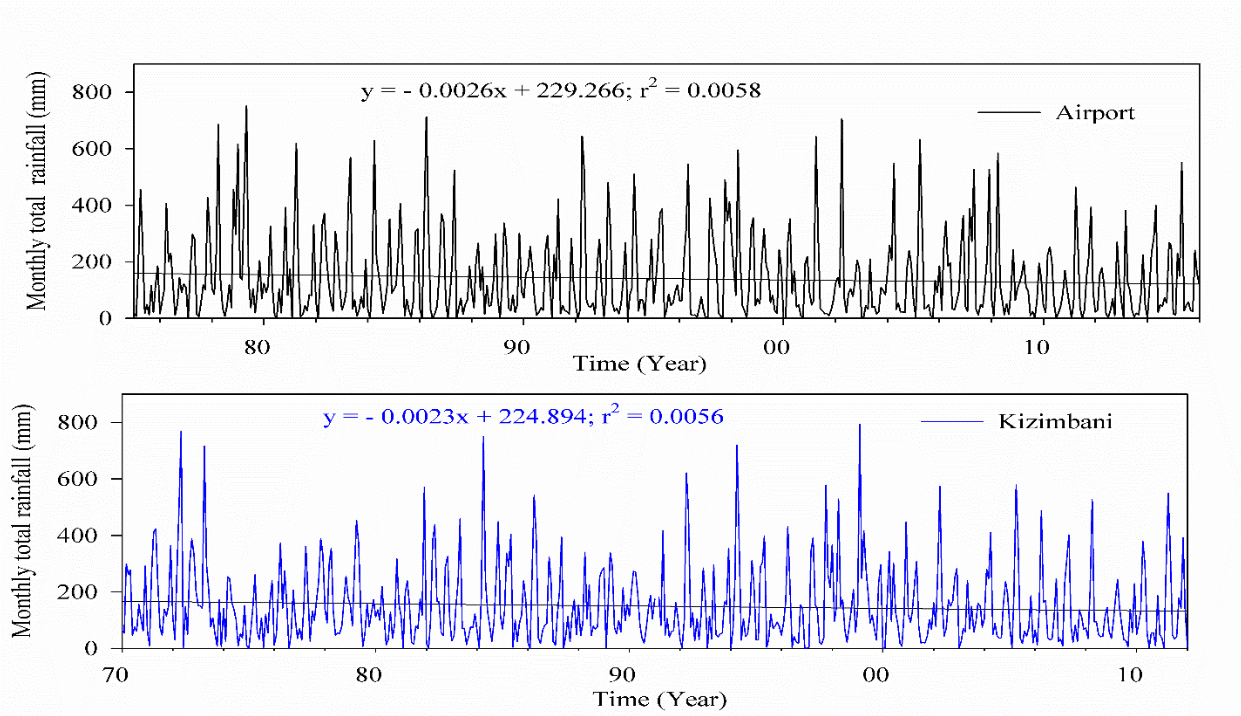

Figure 4: Time series monthly rainfall at AMS and KMS (mm)

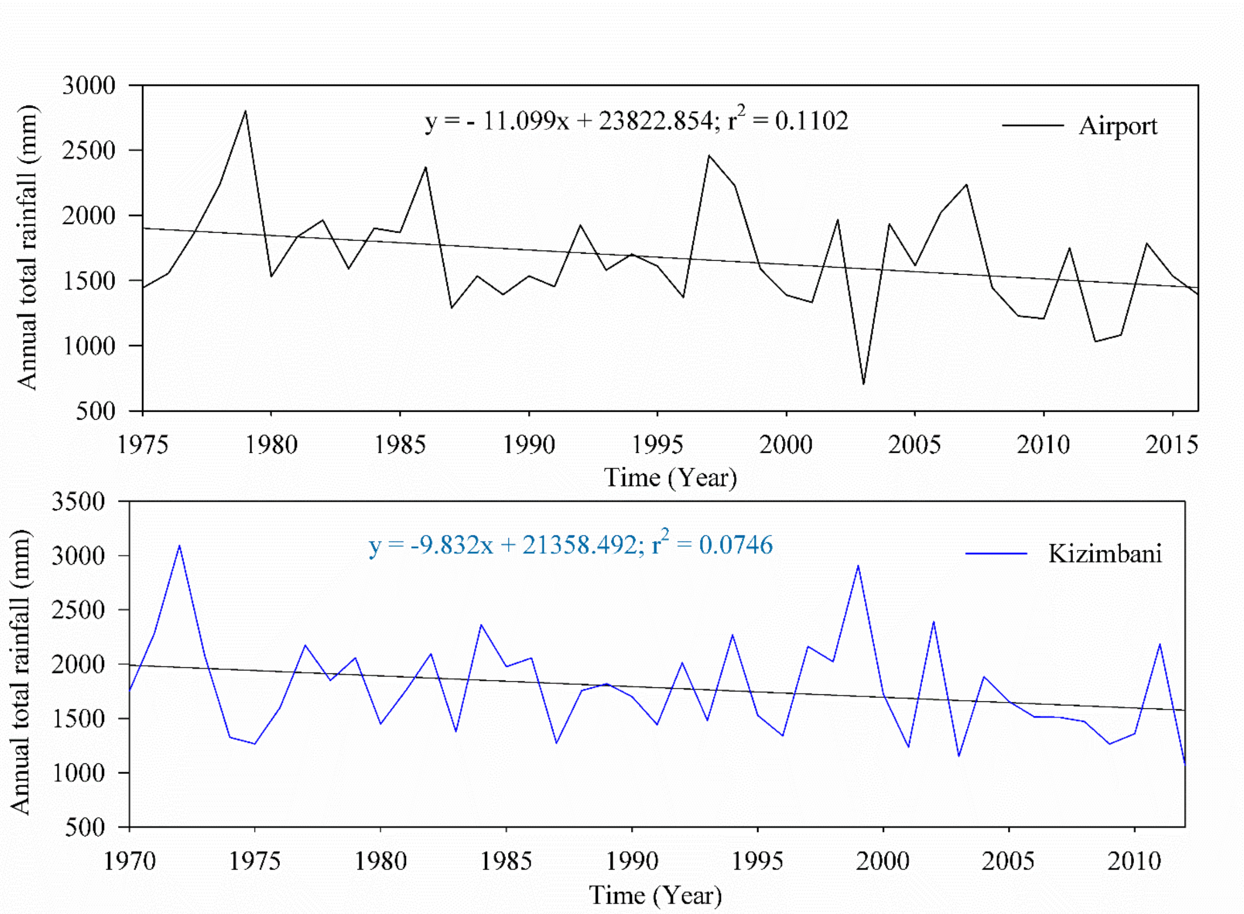

Figure 5: Time series annual rainfall at AMS and KMS (mm)

4.1.2 Temperature

According to the Zanzibar Water Supply and Sanitation Project; in recent years, the impacts of climatic changes can be felt on the water resources of Zanzibar. Variations in temperature may affect groundwater levels due to freeze-thaw and the temperature dependency surface tension, air solubility and air density (Healy & Scanlon, 2010). Also, the temperature is a key driver for other climate parameters (Charman *et al.*, 2009). Furthermore, increasing temperature changes will eventually affect the occurrence of precipitation. Temperature data collected at Zanzibar Airport station for the past 42 y, showed that both monthly and annual mean minimum temperature (T_{min}) and mean maximum temperature (T_{max}) has been increasing. However, the T_{min} values seem to be more alarming than the T_{max} ones (Figures 6 and 7). Thus, local warming would, in turn, have an implication on the amount of groundwater recharge rate. The Pearson correlation values indicated that although the mean monthly maximum temperature was increasing but the increment was not significant, whereas the mean monthly minimum temperature showed a slightly significant increment.

Moreover, as Fig. 5 indicates, there was a significant temperature increase for the mean annual temperature maximum and minimum temperatures. Also, according to the villagers, most of the sampled boreholes for this study have been experiencing a decrease in yields that might be attributed to increasing temperatures and subsequent evaporation.

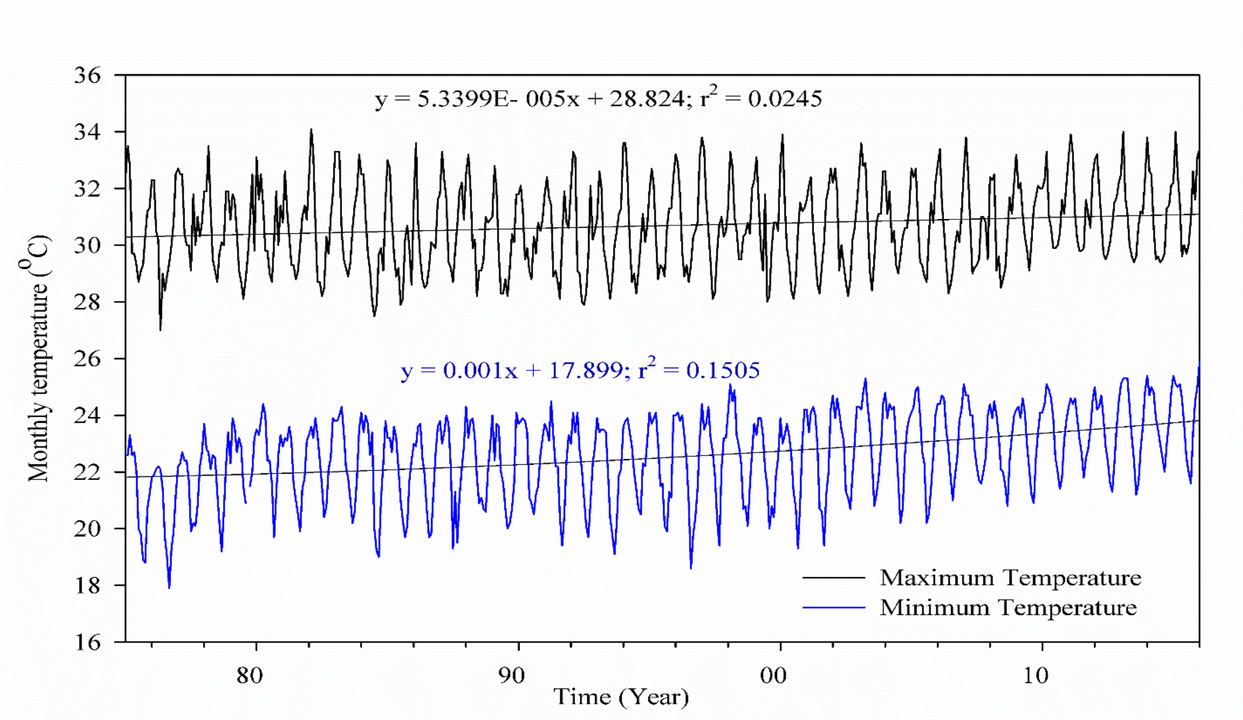

Figure 6: Time series of monthly mean maximum and minimum temperature at AMS (^{0}C)

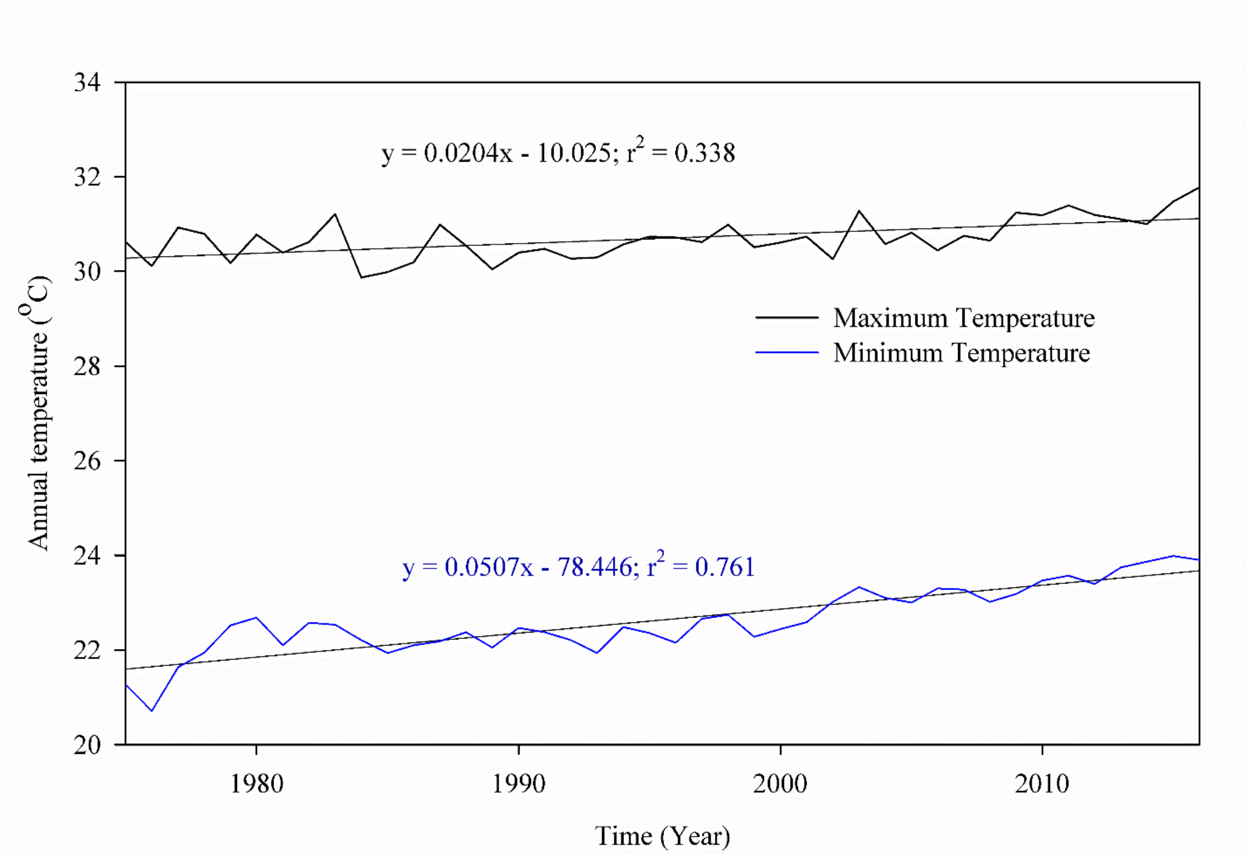

Figure 7: Time series annual mean maximum and minimum temperature at AMS (^{0}C)

4.2 Groundwater recharge estimation

Water recharges the groundwater system by the percolation of water from precipitation and then flows to the stream through the groundwater system (Sophocleous, 2002). Understanding the spatial variations of groundwater recharge is vital for proper water management that prompts feasible improvement and conservation of groundwater assets (Moon *et al.*, 2004). In this study, the average recharge was found to be 7.85mm/y (1.79x $10^6 m^3/y$) (Table 3) which represents about 7.025% of annual rainfall. Figure 8 presents one of the samples of the groundwater hydrograph from Mwembemchomeke for estimating groundwater recharge using the WTF method.

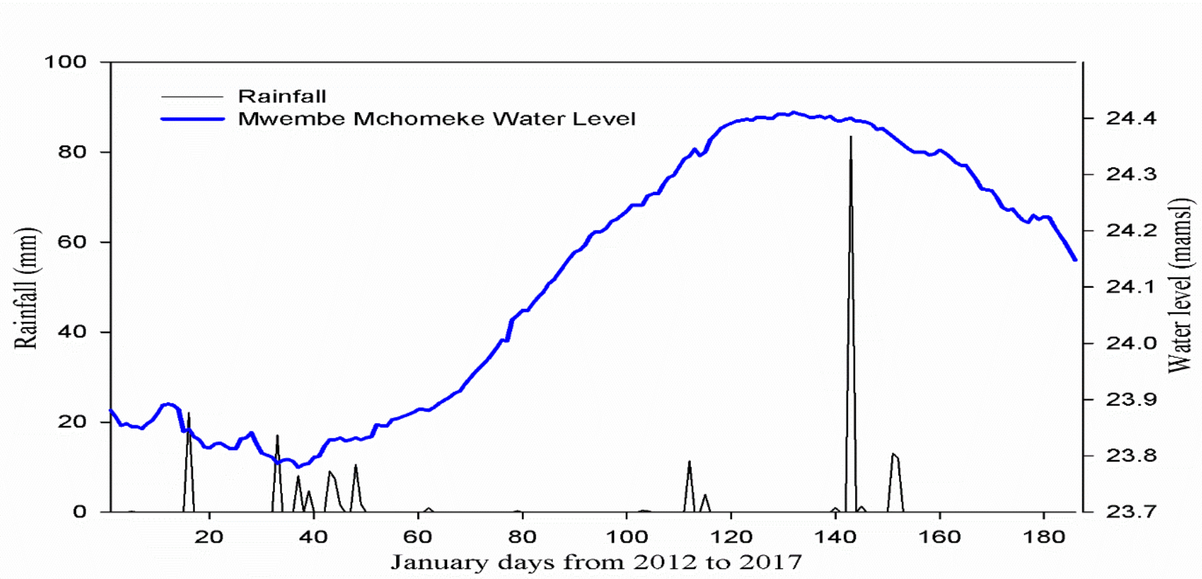

Figure 8: Water level fluctuation for Mwembemchomeke borehole

Table 3: Annual estimated recharge

Year	**Annual rainfall(mm/y)**	**Area (km^2)**	**Recharge (mm/y)**	**Recharge ($x10^6$)(m^3/y)**	**Annual rainfall (%)**
2012	85.86	227.463	7.05	1.60	8.21
2013	90.13	227.463	9.30	2.12	10.32
2014	148.68	227.463	10.88	2.47	7.32
2015	127.97	227.463	10.49	2.39	8.19
2016	115.88	227.463	9.37	2.14	8.10
2017	166.53	227.463	0	0	0
Total average estimated recharge			**7.85**	**1.79**	**7.025**

4.3 Recharge, SY and WTF

From the recharge results in Table 3, sustainable yield values for each category were computed. The results are shown in Table 4. From these results, it seems that for each year the study area is over-pumped. The current total average groundwater pumpage is around $2.49x10^6$ m^3/y. According to Ponce (2007a), groundwater pumpage should not exceed $1.25x10^6$ m^3/y, 0.72 x 10^6 m^3/y and 0.18 $x10^6$ m^3/y, if it has to be sustainable under, respectively, LC, AP and RC categories. Going by the current pumpage, it is clear that the current usage is unsustainable.

Table 4: Percentage sustainable yield categories based on water table fluctuation values

Year	Current pumpage ($x10^6$ m^3/y)	Current Estimated recharge ($x10^6$ m^3/y)	Least conservative (LC) 70% Recharge ($x\ 10^6\ m^3/y$)	Average percentage (AP) 40% Recharge ($x10^6\ m^3/y$)	Reasonable conservative (RC) 10% Recharge (x106 m^3/y)
2012	1.62	1.60	1.12	0.64	0.16
2013	2.08	2.12	1.48	0.84	0.21
2014	3.03	2.47	1.73	0.99	0.25
2015	3.06	2.39	1.67	0.96	0.24
2016	2.48	2.14	1.49	0.86	0.21
2017	2.66	*N.A.	*N.A.	*N.A.	*N.A.
Standard	2.49	1.79	1.25	0.72	0.18

*N.A. = Data not available

4.4 Groundwater abstraction rates

The total average groundwater pumpage from all sources is $2.49x10^6$ m^3/y, estimated from the data as shown in Table 5, which is higher than the rate of recharge about 1.79x $10^6 m^3/y$. This means that groundwater resources are currently over-pumped. The over-pumping condition from all mentioned sources also can be observed due to variations of pumping rates in monthly and annually as shown in Fig. 9 and Fig. 10 respectively. The mentioned sources supply water for domestic purposes, small irrigation purposes and other development activities. Mato (2015) recommended that, the establishment of a long-term monitoring program will help to control the problem of groundwater pumpage. In Unguja, a number of groundwater sources were recently abandoned due to drying and saline water intrusion. The information gathered from ZAWA suggests that between 2002 and 2005 about 15 pumped wells have to be abandoned due to salinity or depletion problems.

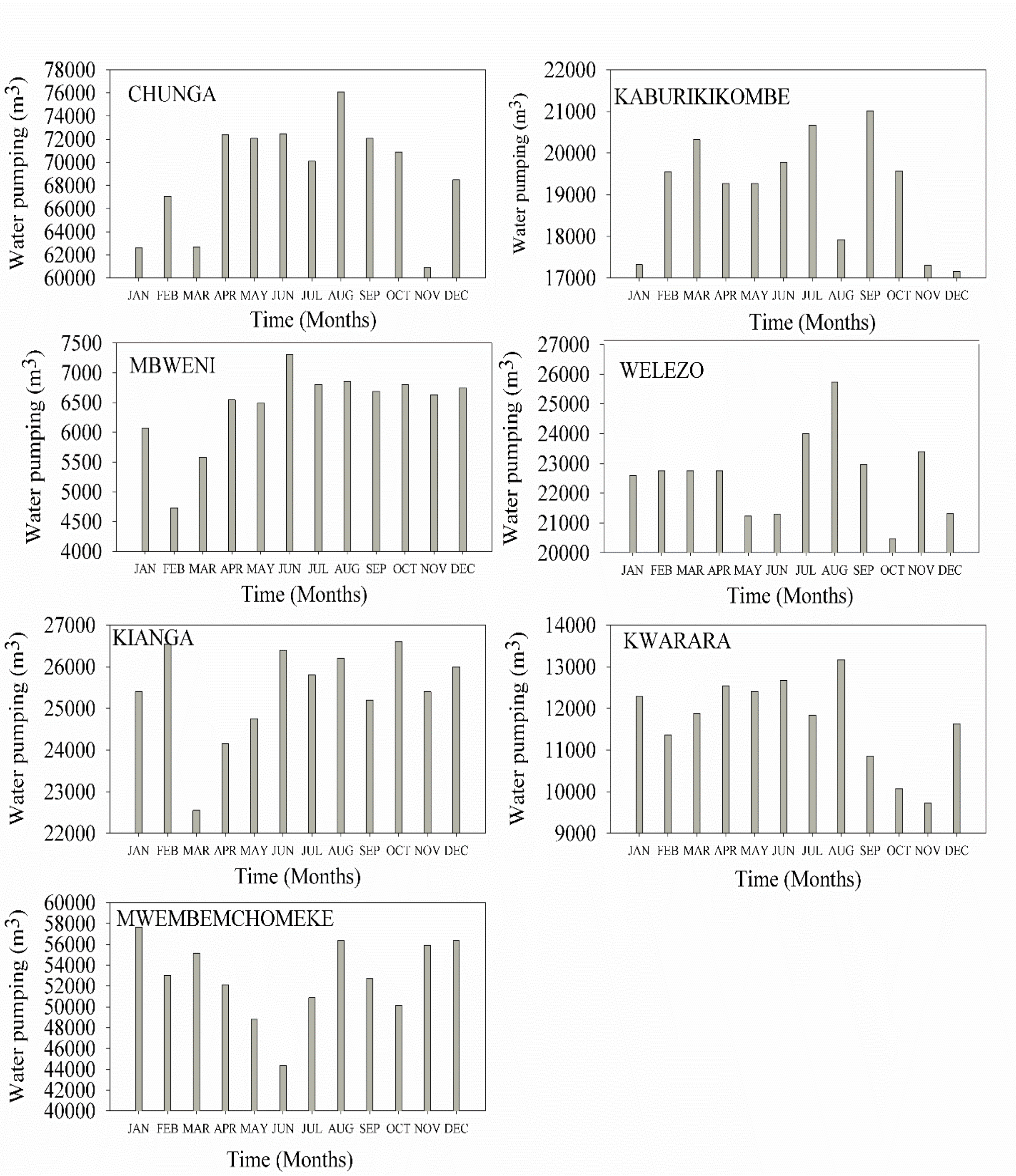

Figure 9: Monthly variations in pumping rates (m^3) for the seven (7) sampling sites on Zanzibar Island

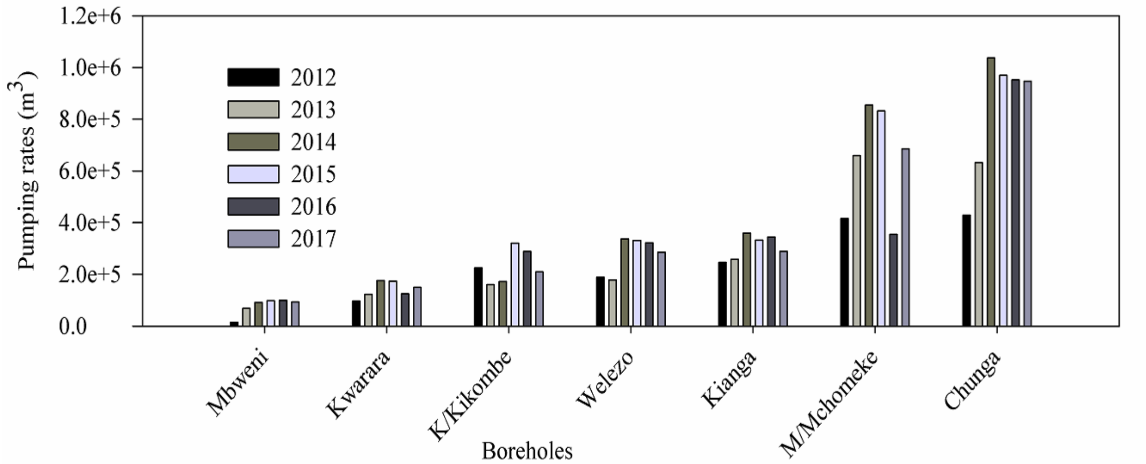

Figure 10: Annuall variations in pumping rates (m^3) for the seven (7) sampling sites on Zanzibar Island

Table 5: Pumping rates per year the seven sampling stations for years 2012 – 2017

Sampling station	Pumping rates (m^3) Year					
	2012	**2013**	**2014**	**2015**	**2016**	**2017**
Mbweni	14280	68340	91120	97920	99280	92480
Kwarara	96600	122700	176400	173400	124500	149000
Kaburikikombe	225060	159660	171600	321000	288100	209300
Welezo	188888	178200	337200	331200	321600	285600
Kianga	246000	258000	360000	332400	344400	289200
Mwembemchomeke	416230	658880	854400	832000	353840	685040
Chunga	429000	632040	1036800	969200	952000	947200
Mean value	1616058	2077820	3027520	3057120	2483720	2657820
± SD	153068	245075	366904	331490	283030	315459

4.5 Integrated water balance (IWB)

Table 6 summarizes the results of IWB, which is vital for assessing local hydro-dynamic features. The IWB values enable a rational assessment and comparisons of magnitudes of inflowing and outflowing terms and provide key information for sustainable groundwater abstraction. The mathematical relationships offer room for improvement in the balance to accommodate any future changes in the system such as increasing/decreasing abstractions or recharges. From the computations of IWB, the total pumpage would contribute to 139.23% of recharge and 39.23% was lost as discharge.

Table 6: Integrated water balance results based on current water table fluctuations (recharge) and pumpage

Year	Water balance component (m^3/year)	Magnitude (+ or -) (m^3/year)	Fractions total recharge (%)
2012	Recharge	+1603614	
	Pumpage	-1616058	100.77
	Discharge to	-12444	0.77
2013	Recharge	+2115405	
	Pumpage	-2077820	98.22
	Discharge to	+37585	1.78
2014	Recharge	+2474797	
	Pumpage	-3027520	122.33
	Discharge to	-552723	22.33
2015	Recharge	+2386086	
	Pumpage	-3057120	128.12
	Discharge to	-671034	28.12
2016	Recharge	+2135877	
	Total pumpage	-2483720	116.29
	Discharge to	-347843	16.29
2017	Recharge	0	
	Total pumpage	2657820	No fraction
	Discharge to	None	
Total average	Total Recharge	+1785963	
	Total pumpage	-2486676	139.23
	Total discharge	-700713	39.23

4.6 Groundwater quality

Freshwater that does not contain excessive nutrients, organic and inorganic pollutants is desirable for human and ecosystem health (WHO, 2011). Contamination of groundwater sources in sub-Saharan Africa poses a threat not only to Africa's human health but also to Africa's pristine environments (Elisante & Muzuka, 2017). Uncontrolled pollutants from upstream sources may gradually find their way into boreholes, leading to increased levels in environmental parameters such as nitrate, sulphate and various trace elements (Mohamed *et* *al.*, 2014). The situation is even more exacerbated in coastal areas where threats of seawater intrusion and water table fluctuation are immense.

In the present study, water quality data from ZAWA were compared against the WHO standards. Most of the water quality parameters were found to be within the WHO limits. However, an increasing trend was observed especially for parameters related to seawater intrusion. In Kianga, Mbweni and Chunga the increasing trends in the contaminants may be attributed to long-term groundwater pumpage. Data collected at Kaburikikombe showed indications of seawater intrusion due to high electrical conductivity values of up to 1321 µs/cm and high chloride levels of up to 1299.17 mg/L. Moreover, in Table 7 and Fig. 11 high levels of nitrate of up to 68.47 mg/L were observed at Mbweni borehole which exceeded the WHO limit (Table 8).

Table 7: Statistical results of G.W quality parameters (all units are in mg/l except EC (µS/cm), salinity (ppt) and pH which is unitless

PAR	MBWENI				KWARARA				K/KIKOMBE				WELEZO			
	Av.	Min	Max	SD	Av	Min	Max	SD	Av	Min	Max	SD	Av.	Min	Max	SD
$S0_4$	24	21	26	2.65	70.33	69	72	1.53	27.33	26	29	1.53	14.67	14	15	0.58
Cl	259.12	257.7	260.17	1.29	266.1	252.9	277.16	12.26	1299.17	1211.47	1470.29	147.76	112.91	108.97	116.21	3.66
NO_3	68.47	67	70	1.5	21.33	20.9	21.8	0.45	43.13	40	45.3	2.78	10.93	10.6	11.3	0.35
ca	68.93	67.13	70.14	1.59	62.1	57.31	65.73	4.33	85.63	85.36	85.97	0.3	27.71	25.65	30.06	2.22
Mg	21.13	20.72	21.51	0.39	24.3	22.11	27.22	2.63	35.57	33.61	37.67	2.03	9.79	9.6	9.96	0.18
TH	262.9	261.5	263.7	1.22	254.7	254.1	255	0.52	368.67	367	370.5	1.76	114.97	114.5	115.4	0.45
K	4.29	4.27	4.31	0.0208	2.28	2.22	2.35	0.07	4.57	4.52	4.61	0.05	2.68	2.63	2.77	0.08
HCO_3	46.1	45	47.3	1.15	91	90	92	1	145	145	145	0	96	95	98	1.73
Na	30.53	30.2	30.75	0.29	34.95	34.65	35.2	0.28	77.43	76.55	78	0.78	20.13	19.28	20.9	0.81
Temp	28.3	27.9	28.8	0.45	29.61	29.23	29.8	0.33	28.46	28.43	28.5	0.04	29.21	29.2	29.23	0.02
Ph	7.08	7.04	7.12	0.04	7.27	7.23	7.29	0.03	6.77	6.76	6.78	0.01	7.17	7.15	7.21	0.03
TDS	489	488	490	1	523.67	523	524	0.58	857	856	858	1	153.67	153	154	0.58
EC	751.33	751	752	0.58	803.67	802	806	2.08	1321	1320	1322	1	236	235	237	1
Sal.	0.31	0.31	0.32	5.77E-03	0.32	0.31	0.34	0.02	0.63	0.62	0.65	0.02	0.08	0.08	0.09	5.77E-03
DO	7.63	7.61	7.64	0.02	5.63	5.61	5.64	0.02	5.35	5.35	5.36	5.77E-03	6.6	6.54	6.69	0.08

PAR.	KIANGA				M/MCHOMEKE				CHUNGA			
	Av.	Min	Max	SD	Av.	Min	Max	SD	Av	Min	Max	SD
SO_4	0	0	0	0	3.67	2	5	1.53	5	5	5	0
Cl	108.5	107.22	109.95	1.37	102.49	84.22	113.46	15.93	152.08	150.2	153.45	1.69
NO_3	11.93	11.8	12.1	0.15	11.4	11.3	11.5	0.1	12.4	12	12.7	0.36
ca	41.49	40.28	42.13	1.05	48.91	48.74	49.1	0.18	47.75	46.89	48.25	0.75
Mg	25.47	24.8	26.12	0.66	8.11	7.13	8.99	0.93	13.09	12.7	13.61	0.47
TH	196.83	192	200.5	4.37	151.23	149.5	153.2	1.86	157	156	158	1
K	1.39	1.33	1.46	0.07	2.13	2.08	2.17	0.05	2.35	2.26	2.47	0.11
HCO_3	89.33	88	90	1.15	99.33	98	100	1.15	99.67	99	100	0.58
Na	11.61	11.48	11.7	0.11	14	13.93	14.07	0.07	16.69	16.56	16.91	0.19
Temp	28.71	28.65	28.8	0.08	28.62	28.6	28.65	0.03	29.48	28.81	29.82	0.58
Ph	7.19	7.18	7.19	5.77E-03	7.22	7.21	7.23	0.01	7.26	7.24	7.27	0.02
TDS	382.67	381	385	2.08	388.33	386	390	2.08	424.33	423	426	1.52
EC	590	589	591	1	599	598	600	1	655	654	657	1.73
Sal.	0.26	0.25	0.27	0.01	0.25	0.25	0.26	5.77E-03	0.27	0.26	0.27	5.77E-03
DO	7.17	7.16	7.18	0.01	6.22	6.21	6.23	0.01	7.08	7.07	7.08	5.77E-03

Table 8: Water quality Standards for National and WHO

Standards used	Water quality parameters (except for pH, which is unitless and EC, all units in mg/L)										
	EC(μS/cm)	pH	Na^{+}	Ca^{2+}	Mg^{2+}	K^{+}	HCO_3^{-}	Cl^{-}	SO_4^{2-}	NO_3^{-}	TH
National	1500	6.5– 9.2	600	300	100	20	n.m	800	800	75	n.m
WHO	1500	6.5 – 8.5	200	200	150	12	n.m	600	400	50	500

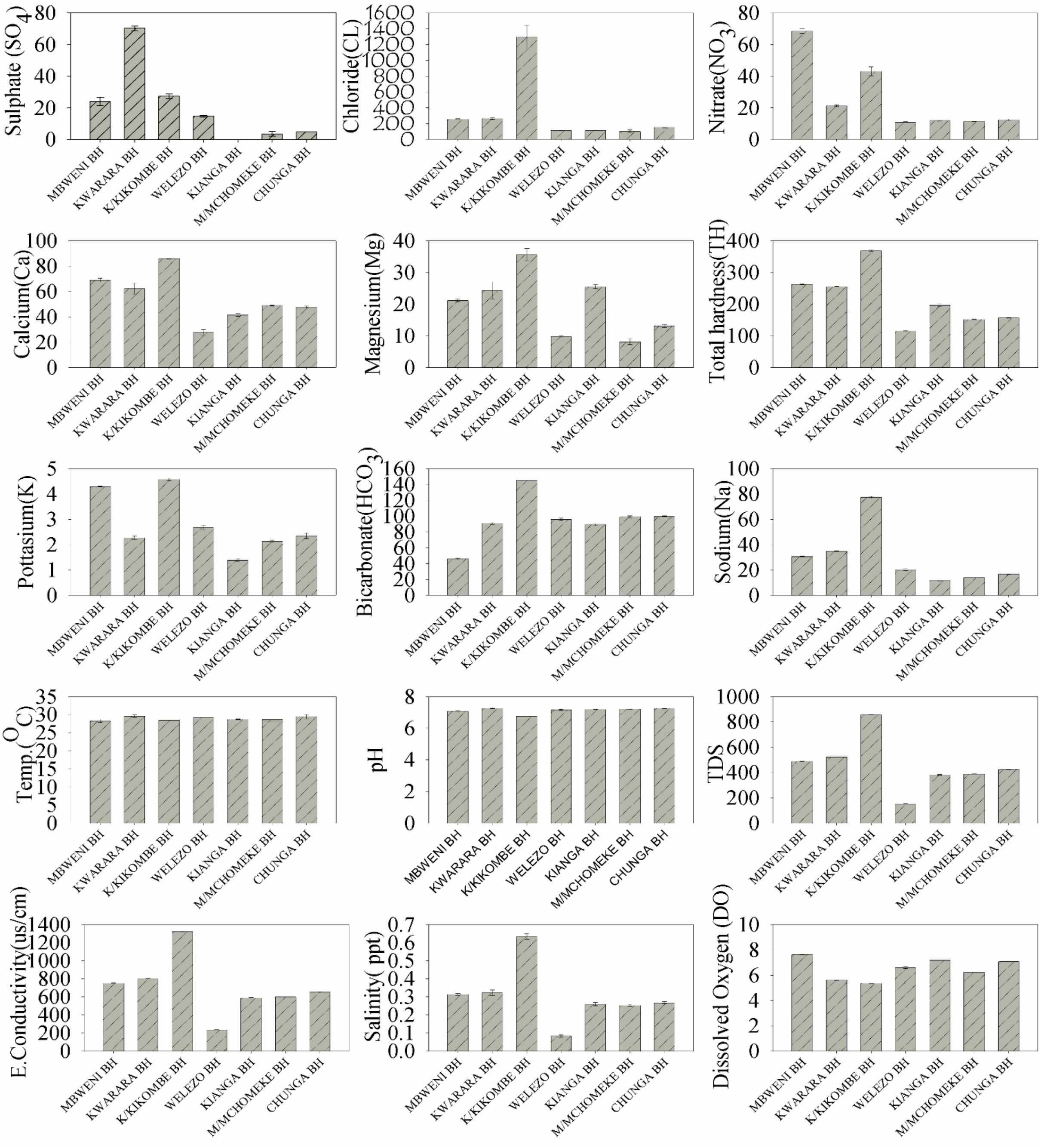

Figure 11: Statistical analysis for water quality parameters

4.6.1 Groundwater quality classification

The piper diagram (Fig. 12) was used in the classification of water quality. A careful examination of the diagram indicates the differences and similarities of water types (Utom *et al.*, 2013). Results of cations from the piper charts showed that all boreholes were calcium magnesium (Ca^{2+}, Mg^{2+}) water type, which exceeded 50% of the total meq/L. On the other hand, the results of anions showed that all seven boreholes were dominated by sulphate

(SO_4^{2-}) and chloride (Cl^-) water type and none of the boreholes were in bicarbonate (HCO_3^-) or carbonate (CO_3^{2-}) water type.

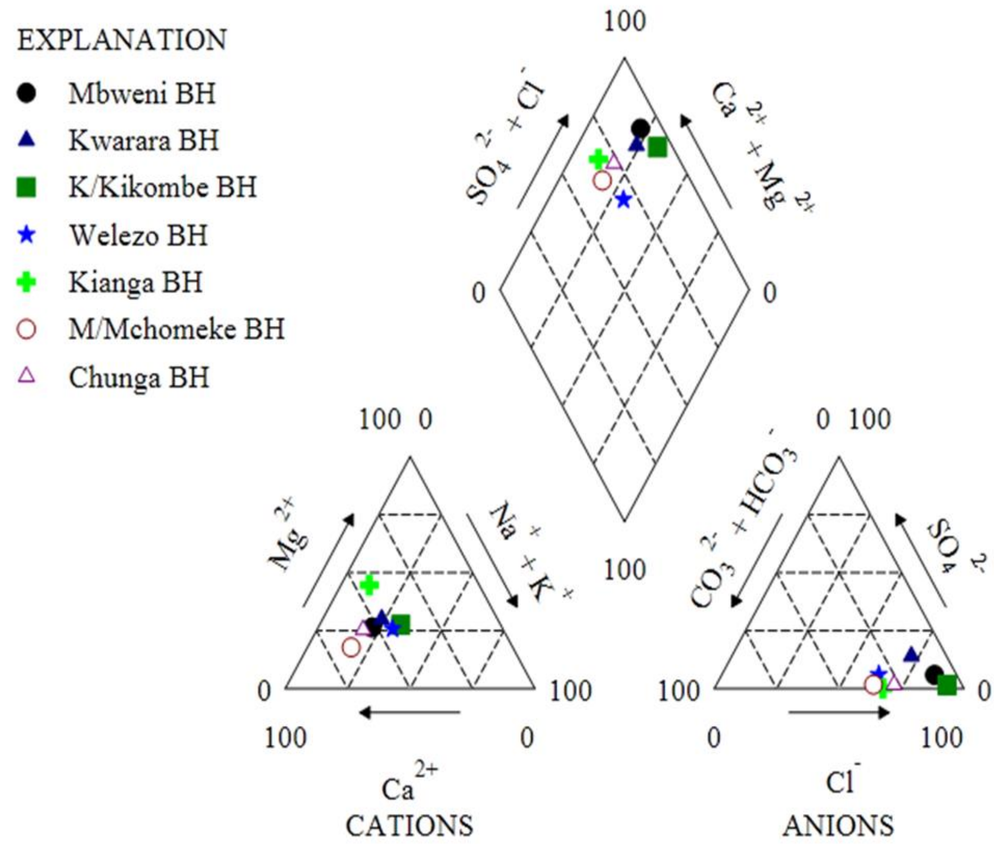

Figure 12: Piper diagram for groundwater chemistry classification

4.6.2 Cluster analysis (dendrogram)

There are six clusters as shown in Fig. 13. The first cluster comprises with Chunga and Mwembemchomeke boreholes having a similarity of 99%. The second cluster comprises with first cluster and Kianga boreholes having a similarity of 99%. The third clusters comprise with Kwarara and Mbweni boreholes having a similarity of 99%. The fourth clusters comprisewith the second and third clusters having a similarity of 98%. The fifth clustercomprisewith the fourth cluster and Welezo borehole having a similarity of 95%. While the sixth cluster comprises with the fifth cluster and Kaburikikombe borehole having a similarity of 85%.

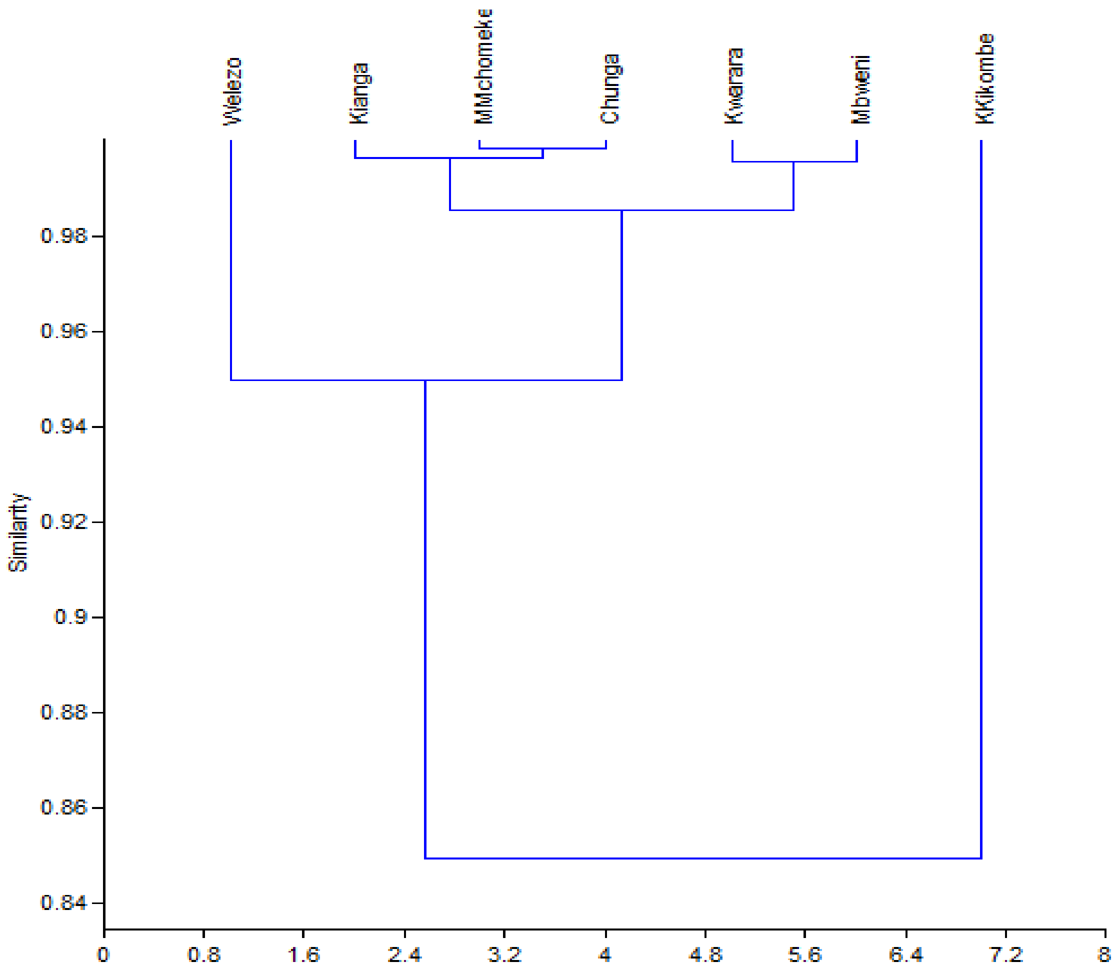

Figure 13: Cluster analysis (dendrogram)

4.7 Groundwater chemistry vs. pumpage

Results for analysis of water quality data from ZAWA and the field water quality data (Fig. 14). All the results indicate that water quality parameters significantly increased with pumping groundwater age. The EC values were high in Kaburikikombe with ZAWA data values indicating EC > 1300 µS/cm. Similarly, field data for the Kaburikikombe sampling point indicate an EC value range of 1320-1322 µS/cm. Total groundwater hardness was high at Kaburi kikombe and Kwarara boreholes. Chloride levels were high in Mbweni, Kianga, and Kwarara sampling points. Sulphate levels were high at Welezo and Kwarara boreholes whereas TDS values were high in Kianga and Chunga boreholes. It is clear from these data that the future outlook of the groundwater pumpage on the island of Zanzibar is not sustainable. There are indications that the groundwater table has gone deeper and saltwater is gradually mixing with groundwater sources.

For water sources and resources of Zanzibar to be sustainable, they must meet the needs of the present population without compromising the ability of future populations to meet their own needs (Bredehoeft & Alley, 2014). As is in all parts of sub-Saharan Africa, the population on the island of Zanzibar is rapidly increasing. With the increasing population, pressure on groundwater sources is also rapidly increasing (Shi *et al.*, 2011). As a result, effects such as saltwater intrusion and elevated levels in environmental pollutants are on the rise.

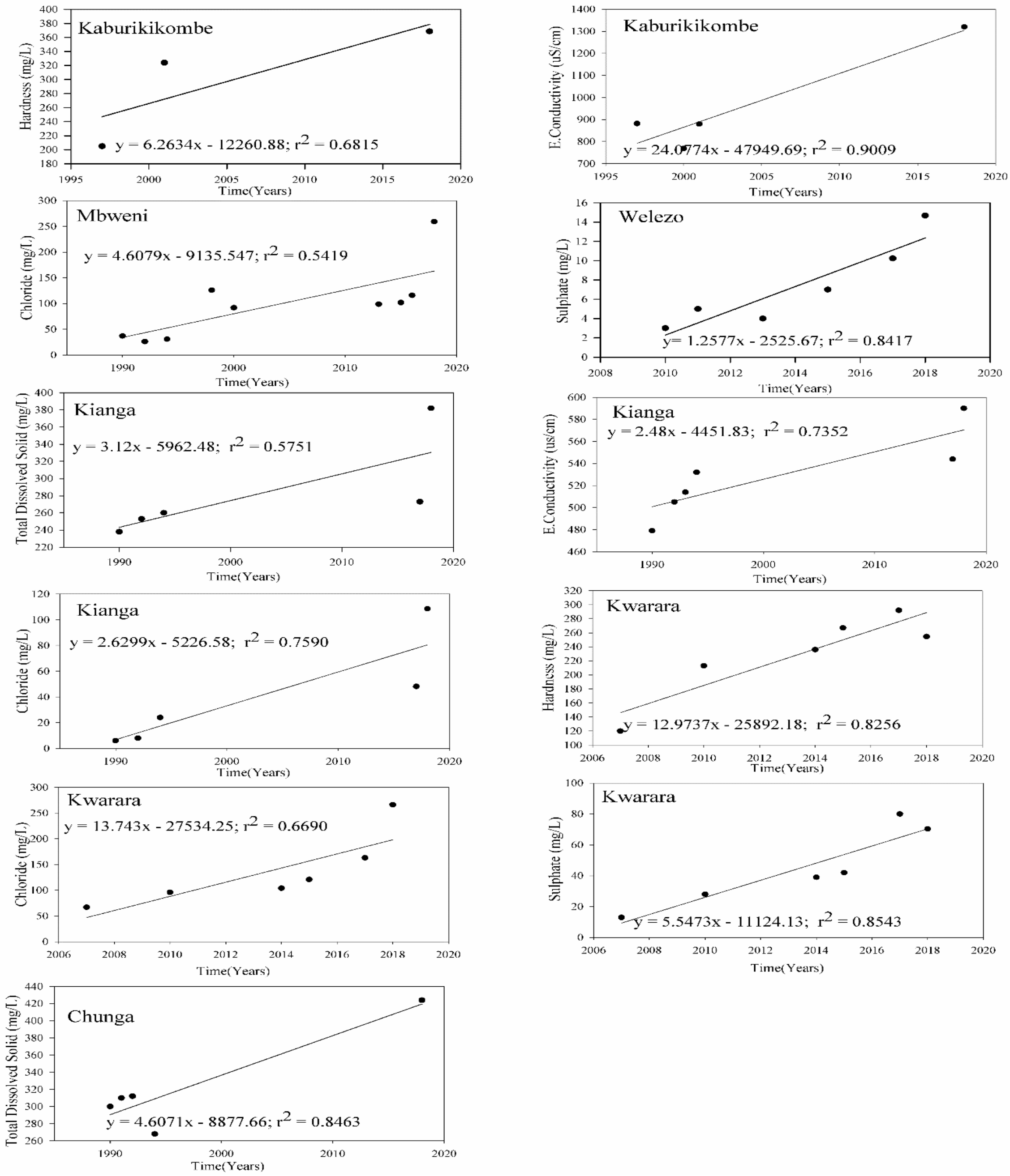

Figure 14: Increment of some historical water quality parameters due to high pumpage

4.8 Projection of future outlook of groundwater supply in Unguja urban West

The projection of future water demand was analyzed by using the regression equation (3) from GenStat Software for 33 years from 2018 to 2050 (Fig. 15). The data of seven years of groundwater abstraction (Table 9), were used as input into the software, where by the seventh year was the average of all six years. Other data computed were abstraction rates, population growth rate, water demand per year and recharge rates.

Where, Y = Outlook = dependent variables while other data were independent variables.

Table 9: Projection parameters

Years	pump rate(*Pr*) (m^3)	Population(*P*)	Water demand (*Wd*)	Recharge(*R*) (m^3)
2012	1616058	183127	21900	1603614
2013	2077820	191001	22841.70	2115406
2014	3027520	199215	23823.89	2474797
2015	3057120	207781	24848.32	2386087
2016	2483720	216715	25916.80	2135878
2017	2657820	226034	27031.22	0
2018	**2486676**	**235754**	**28193.56**	**1785963.667**

The regression Equation (3) used was,

$$Y(Outlook) = aWd + bP + cR + dPr + K \tag{3}$$

Where K = Constant

The model results were: $P = 8.362Wd,\ c = 4.85\ 10^{-8}$

$a = 0.00097667, \quad K = 1991.261, \quad d = 4.97x\ 10^{-8}$

$$Y = 0.00097667Wd + 8.362Wd + 4.85x10^{-8}R + 4.97x\ 10^{-8}\,\mathrm{Pr} + 1991.261$$

The predictions are based on the mean value for 2018 from the previous year from 2012 to 2017

$$Y = (8.362 + 9.767\ x\ 10^{-4})Wd + 4.85x10^{-8}x1785963.67 + 4.97x\ 10^{-8}x2486 + 1991.261$$

$$Y = (8.362 + 9.767\ x\ 10^{-4})Wd + 1991.471$$

$$Wd = \frac{Y - 1991.471}{8.363} \tag{4}$$

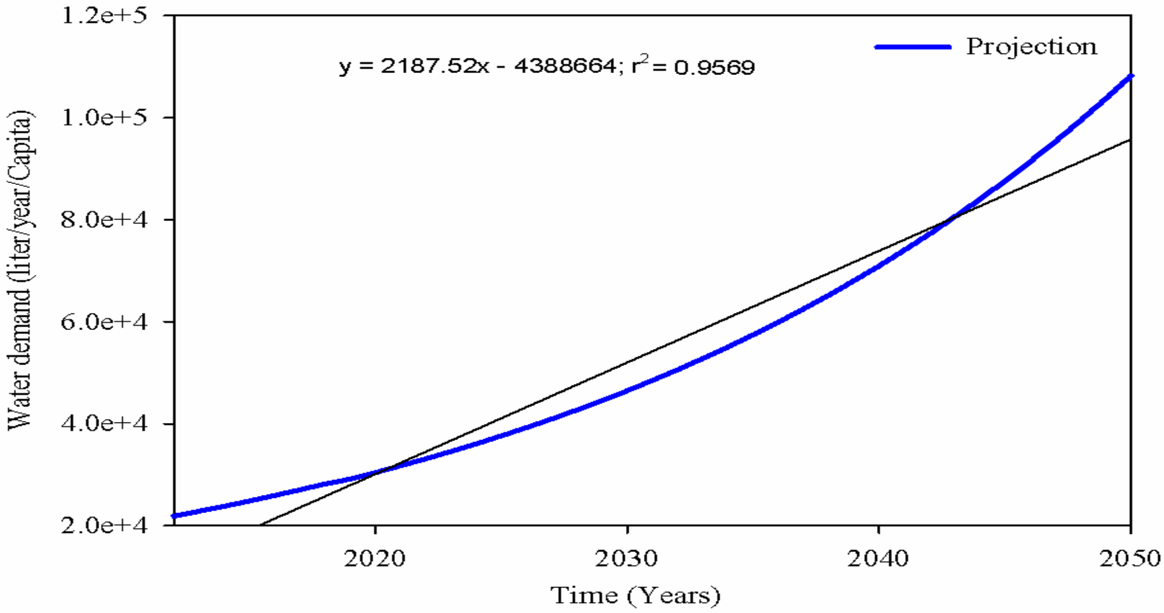

Figure15: The projection for future water supply in Zanzibar

The water demand (liter/year/capita) was computed by using Equation (4) generated from the results obtained from the GenStat Software. Results in Fig. 15 shows that the usage of water per capita per year will significantly increase. Moreover, the water demand is expected to worsen as the population increases.

4.9 The Kilimanjaro concept as suitable solution for water supply in Zanzibar

Qi *et al.* (2019) reported that the Kilimanjaro concept advocate for the conception of a regional network to harvest, store and consequently use rainwater from roof tops and other clean surfaces. One of the advantages of harvesting rainwater is an artificial recharge in groundwater sources to increase the groundwater storage in aquifer and consequently use during the dry season especially in coastal areas, artificial recharge prevents saltwater intrusion. Moreover, artificial recharge prevents the groundwater source to fail and depletion due to over pumping. As in this present study, Zanzibar Island, especially the Urban West region, the sources are already over-pumped. Therefore, the Kilimanjaro concept could be adopted as a suitable solution for water supply.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Statistical analyses of the major climatic parameter i.e. rainfall and temperature of Zanzibar has been presented in this study. There was a similar trend in rainfall and major alterations, irrespective of the differences in the longevity of data. From the current study, we could see that a further decrease in precipitation could adversely affect the recharge of groundwater resources that supply fresh water on the island. For temperature, it was observed that both monthly and annual mean minimum temperature (T_{min}) and mean maximum temperature (T_{max}) have increased over the applied time series. Also, most of the boreholes experienced a decrease in yield due to increasing temperatures and evaporation.

The results showed that the average groundwater pumpage is higher than the average recharge rate. It has been observed that the concentration of some contaminants such as total hardness, electrical conductivity, total dissolved solids, chloride and sulphatewere increasing with increased pumping age. All boreholes were calcium magnesium of (Ca^{2+}, Mg^{2+}) water type while the results for anions were dominated by sulphate (SO_4^{2-}) and chloride (Cl^-) water type.

5.2 Recommendations

Population growth rate in Unguja Urban West seems to increase from year to year as can be seen this in the projection from 2018 to 2050 (Fig. 15). As the population increases, also the water demand per capita per year increases. Therefore, water demand should meet the requirements of all sectors. The alternative sources should be in place so as to overcome the challenges. A controlled infiltration of harvested rainwater is suggested as a sustainable solution for salt intrusion as well the balance way of recharge and abstraction rate in Zanzibar and other islands. Pumping of groundwater requires much investment authorities andwell-informed planning such as knowing where the borehole to be located and how they are to be constructed. Viability studies should be well conducted before the borehole construction so as to understand the aquifer condition, water quality and any waste disposal option to ensure the sustainability of freshwater resources for both human use and ecosystem. This will helpto prevent or minimize harmful impacts on groundwater. Moreover, in sustainable yield, the AP category of SY is better to be proposed which would ensure at least 60% of recharge water is left in the aquifer as environmental water flow and protect it from unwanted aquifer overdraft and land subsidence.

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RESEARCH OUTPUTS

Research publication

Assessment of the impact of groundwater pumpage on water supply sustainability in Zanzibar, Tanzania

Poster presentation

Assessment of the Impacts of groundwater pumpage on the future water supply sustainability in Zanzibar, Tanzania

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Introduction

- Nearly 1.1 billion people have a shortage of clean and safe water for use, and often rely on unsafe ground or surface water supply systems (Peter-Varbanets *et al.*, 2009)
- In Africa, over 300 million people have no access to safe drinking water (MacDonald *et al.*, 2012)
- In Tanzania, water provision to the majority of the population is still a challenge. Over 89% of Tanzanians collect water from public places such as wells, streams, and watersheds which is sometimes not safe for human consumption (Taylor *et al.*, 2013))
- On Zanzibar (Unguja) Island, local communities depend solely on the limited groundwater supply for their freshwater needs, and the groundwater table is gradually being contaminated by salt intrusion (Mato, 2015)

Main objective

- To assess the impacts of groundwater pumpage on the future of water supply sustainability in Zanzibar.

Specific objectives

- To estimate the balance between groundwater recharge and water abstraction rates
- To assess the impact of groundwater pumpage on water quality
- To project the future outlook of groundwater supply in Zanzibar

Significance

- There is pressure on available water sources in Zanzibar. Some of the sources are already abandoned due to salt intrusion as a result of long-term pumpage
- Therefore, a need has arisen to understand the impacts of groundwater pumpage in terms of long-term variabilities in groundwater quality and quantity
- The information obtained in the present study will give a clear picture of the current situation on water availability and water quality issues on the island.

Methods

- Severe boreholes studied from urban west zone namely; Kaburikikombe, Chunga, Mbweni, Kwarara, Mwembemchomeke, Welezo and Kinanga
- Water table fluctuation method for estimating the recharge amount per year as expressed by (Healy & Cook, 2002)
  $R = Sy \times \Delta H$
- By conducting the abstraction rates for every months on the studied boreholes and estimated the abstraction rates per year using Microsoft excel
- Rainfall and Temperature data statistically analyzed using SIGMA PLOT software and studied the variation of rainfall due to temperature change
- Also in case of water quality data, existing water quality data from ZAWA conducted
- The experimental water quality data during the present study were also observed for all seven sources

Results 1

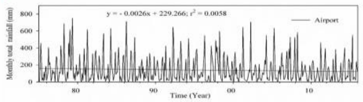

Figure1: High variation of rainfall due to high temperature change (mm)

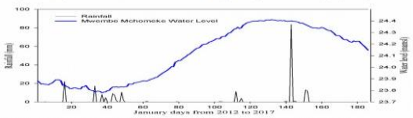

Figure 2: Recharge estimated sample at mwembemchomeke borehole

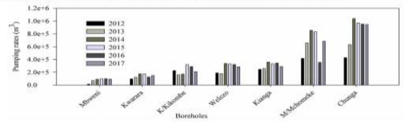

Figure 3: Estimated abstraction rate per year

Results 2

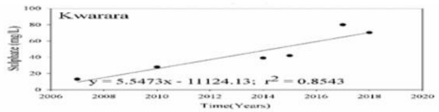

Figure 4: Sample for incremental parameter (sulphate) from year to year at Kwarara borehole

The results show that

- High variation of rainfall due to high variation of temperature
- The abstraction rate is higher than the pumping rate
- By comparison from existing water quality data and the experimental data from the present study. It seems some of the parameter indicate salt intrusion due to overpumping

Conclusion

- There was a similar trend in rainfall trend in rainfall and major altrations, irrespective of the differences in the longevity of the data. From the current study, it seems that, a further decrease in precipitation could adversely affect the recharge of groundwater resources that supply freshwater on the Island
- The results showed that, the average groundwater pumpage (2.49×10^6 m^3/y) is higher than the average rate ($1.79 \times 10^6 m^3/y$).Therefore the area is already overpumped
- There are some indication of salt water intrusion due to overpumping

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