ASSESSMENT OF GROUNDWATER ABSTRACTION AND HYDROGEOCHEMICAL INVESTIGATION IN ARUSHA CITY, NORTHERN TANZANIA

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A Dissertation Submitted in Partial Fulfilment of the Requirements for the Degree of Doctor of Philosophy in Hydrology and Water Resources Engineering of the Nelson Mandela African Institution of Science and Technology

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ABSTRACT

In this work geological and hydrogeochemical data, radioisotopes and stable isotopes, and groundwater hydrographs were used to assess the groundwater abstraction trends and hydrogeochemical characteristics of Arusha wellfield in Arusha city. Groundwater salinity in terms of conductivity (EC) was also used to delineate salinity occurrence and distribution in different parts of Tanzania including Arusha where this study was carried out. The hydrogeochemical results revealed Na-K-HCO_3 water type. Water-rock interaction seems to be the main process determining the groundwater chemistry in the study area. The analysis of geological sections showed two potential aquifers, volcanic sediment and weathered/fractured both of which yield water with high fluoride. Eighty two (82) percent of the analyzed groundwater samples indicated fluoride concentrations higher than WHO guidelines and Tanzanian drinking water standards (1.5 mg/l). Groundwater hydrographs indicated significant groundwater depletion. Water level decline of about 1.0 m/year and discharges reduction of 10 to 57% were observed from the year 2000 to 2017. The radiocarbon isotope signatures showed that groundwater with mean age of 1400 years BP to modern was being abstracted from the wellfield. Recently recharged water was also evidenced by high ^{14}C activities (98.1±7.9 pMC) observed in spring water. Both groundwater hydrographs and isotope signatures suggest that the Arusha wellfield is already stressed due to groundwater over-abstraction. Through groundwater salinity mapping, it was revealed that generally Arusha has fresh groundwater but with relatively high electric conductivity (1000-2000 µS/cm). The high salinity levels are partly due to dissolution of trona (evaporate mineral) commonly found in the East African Rift System. It was further revealed that lack of reliable hydrogeological information including interaction between surface water and groundwater hinders water resources management efforts particularly issuance of water use permit. Based on the findings of this study, it is recommended to carry out groundwater flow patterns modelling to show how unregulated drilling affects the deep wells currently depletion problem.

DECLARATION

I, Nyamboge Chacha Makuri 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.

Nyamboge Chacha **Date**

The above declaration is confirmed

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Name of Supervisor (Posthumous)

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CERTIFIATION

This is to certify that the dissertation entitled, "Assessment of groundwater abstraction and hydrogeochemical investigation for sustainable water resources utilization in Arusha City, Northern Tanzania " submitted by Nyamboge Chacha Makuri (P111/T.13) in partial fulfilment of the requirements for the award of Doctor of Philosophy in Hydrology and Water Resources Engineering (HWRE) of Nelson Mandela African Institution of Science and Technology (NM-AIST), Tanzania is an authentic work carried out by him under my guidance.

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DEDICATION

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AAS	Atomic absorption spectrometer
ANOVA	Analysis of variance
APHA	American Public Health Association
AUWSA	Arusha urban water supply and sanitation authority
AWWA	American Water Works Association
BP	Before present
CFC	Chlorofluorocarbon
COSTECH	Commission for science and technology
DIC	Dissolved inorganic carbon
EARS	East African Rift System
EC	Electric conductivity
EMA	Environmental management Act
ESM	Electronic supplementary material
GIS	Geographic information system
GMWL	Global meteoric water line
GPS	Global positioning system
HDPE	High density polyethylene
HU	Housing unit
ITCZ	Intertropical convergence zone
LMWL	local meteoric water line
MET	Weather station
NBS	National bureau of statistics
PAST	Paleontological Statistics
PBWB	Pangani basin water board
PBWO	Pangani basin water office
PDB	Pee Dee Belemnite
pMC	percent modern carbon
SID	Sample ID
SPSS	Statistical package for social sciences
STDEV	Standard deviation
SWL	Static water level
TBS	Tanzania Bureau of standards

TDS	Total dissolved solids
TMA	Tanzania meteorological agency
TMWB	Thornwaite Mather Water balance
TU	Tritium Units
URT	United Republic of Tanzania
USA	United States of America
USD	United States Dollar
VSMOW	Vienna Standard Mean Ocean Water
WB	World Bank
WEF	Water Environmental Federation
WHO	World health organization
WRM	Water resources Management

CHAPTER ONE

INTRODUCTION

1.1 Background of the problem

Fresh groundwater which is about 0.61% of the world's water resources and 98% of fresh water resources (ice caps and glaciers excluded) has a vital role for socioeconomic development and ecosystem integrity (Carpenter, Fisher, Grimm & Kitchell, 1992; Foster & Chilton, 2003). Under the stressed and continuously changing global climate mainly caused by human activities, groundwater reserve seems to be the only reliable source of water supply in terms of quality and availability at any one time (Aeschbach-Hertig & Gleeson, 2012; Franco *et al*., 2018). It's well known that larger cities in the world and intensive irrigated agriculture in semi-arid and humid regions depend mostly on groundwater as the main source of water supply (Konikow & Kendy, 2005; Doell *et al*., 2014). This is because surface water is highly vulnerable to climate change owing to prolonged drought, and quality deterioration due to anthropogenic influence (Foster & Chilton, 2003). Also fresh groundwater has been estimated to be about 100 times more plentiful than fresh surface water (Fitts, 2002). Large groundwater abstraction is reported in both developed and developing countries such as USA, Europe, China, India Iran and Pakistan. The estimated total global abstraction is approximately 734 ±82 km^3 per year (Konikow & Kendy, 2005; Wada *et al*., 2010). Despite the economic and ecological value of groundwater, its reserves are declining from local, regional to global scales.

Groundwater depletion has been caused by intensive abstraction due to increasing water demand as a result of population growth and socioeconomic development which is accompanied by industrialization (Konikow & Kendy, 2005; Giordano, 2009; Aeschbach-Hertig & Gleeson, 2012; Bakari *et al*., 2012a; Famiglietti, 2014; Russo & Lall, 2017). Climate change has been reported to intensify the problem in some regions of the world including Africa and Brazil (Döll, 2009; Russo & Lall, 2017). Some of the groundwater depletion effects include decreasing well yields, rising pumping costs, water quality deterioration and damaging of aquatic ecosystem (Konikow & Kendy, 2005; Sishodia *et al*., 2017). Since the problem has been a global issue, a better understanding of the status of different exploited aquifers and appropriate management solutions worldwide is inevitable. Otherwise the problem of water scarcity, food security and sea level rise which have been reported as some of the groundwater depletion effects (Aeschbach-Hertig & Gleeson, 2012) will spread to areas that could have avoided the risk by taking prior measures.

Although Tanzania has many surface water resources such as large fresh lakes and rivers, groundwater has been playing crucial role in domestic, industrial and irrigation supplies. The rural areas and major towns and municipalities in central and northern regions which are characterized by semi-arid to humid climate depend largely on groundwater abstraction as the main source of water supply (Kashaigili, 2010; Taylor *et al.*, 2013). It is estimated that about 50% of total groundwater abstracted in the country is used to supply rural areas mainly for domestic purpose whereas, 10% is being consumed in urban areas (Kashaigili, 2010). Arusha, where the current study was conducted, is one of the regions which depend largely on groundwater as the main source of water supply. Others include Dodoma, Singida and Kilimanjaro (Kashaigili, 2010). In Arusha city, groundwater contributes more than 80% of the water supply for domestic and other uses such as industrial and agriculture (AUWSA, 2014).

Despite the lack of reliable information on the extent of groundwater abstraction, there is evidence of groundwater depletion in the study area. This includes decline of water levels and subsequently yields reduction in wells that have been functioning for more than 20 years (Ong’or & Long-cang, 2007; GITEC & WEMA, 2011). Moreover, an inventory conducted by Pangani Basin Water Office (PBWO) in 2013 revealed more than 400 wells in the study area were drilled without groundwater permit from water resources management authority. This suggests that groundwater abstraction in the area is not adequately controlled to meet the needs of present and future use (Kashaigili, 2010; Van Camp *et al.*, 2014). Therefore, the ongoing groundwater abstraction in the study area needs a thorough investigation to clearly document the current status of the wellfield and provide a better option for future groundwater management.

Groundwater quality is likely to change due to depletion or over-abstraction effect (Konikow & Kendy, 2005). This happens when there is induced leakage from the land surface, confining layers or adjacent aquifers that contain water of inferior quality due to over-pumping. The problem of over-abstraction of groundwater resource has been and will keep increasing as a result of unregulated groundwater development in the study area and all over the country (Custodio, 2002; Reddy, 2005). Fluoride is among critical natural contaminants in groundwater resource particularly in northern Tanzania. In close proximity, its concentrations vary from one source of water to another (e.g., spring and well) depending on the mineralogical composition of the area. According to AUWSA personal communication (2015) several boreholes have been abandoned due to increase in fluoride concentrations exceeding 10 mg/l which is beyond both Tanzanian drinking water standards and WHO guidelines (1.5 mg/l). Despite all these challenges, baseline and monitoring information on the trends of groundwater quality in the wellfield are lacking. This necessitates the need for undertaking hydrogeochemical investigations and establishing spatial variation of groundwater quality in the study area for future groundwater planning and management.

Aquifer storage may be affected by a number of factors other than groundwater over-abstraction (Custodio, 2002). Natural phenomena, such as delayed and transient effects of the aquifer system, earth quakes, tectonic movement and climate change, have been reported in many parts of the world with significant effect in aquifer productivity (Custodio, 2002; Gorokhovich, 2005; Kitagawa *et al.*, 2006; Kløve *et al.*, 2014; Nigate *et al.*, 2017). Due to the complexity and dynamics of hydrogeological processes, knowledge of a particular aquifer system including recharge mechanisms and age of abstracted groundwater is required to inform the cause and extent of the existing problems. Such a situation leaves a number of questions with respect to sustainability of groundwater utilization in Arusha city for present and future water resources development and for avoidance of likely human impacts (drinking water supply) and ecosystem impacts. Such impacts include reduced stream flows and springs drying up and subsequent impacts on water-dependent ecosystems. Among the issues to be addressed are whether groundwater storage depletion is caused by over-abstraction or the aquifer system in the study area is not actively recharged.

Despite having laws and regulations governing groundwater development in Tanzania most wells have been developed without groundwater permit (Kashaigili, 2010). Such practices carried out by individuals and private entities are likely to threaten the sustainability of the aquifers which is the main source of water supply in Arusha city. Because of unregulated drilling activities in the area even the distance limits for sinking wells or boreholes as stated in the Water Resources Management Act (2009) is not adhered to. This has probably affected many production wells currently used for public water supply. The practice may be due to lack of awareness to the community on the likely groundwater depletion impacts. This calls for a comprehensive groundwater management strategy which can only be realized by generating key information such as physical and chemical frameworks, hydrological and hydrogeological setting of the wellfield (Alley *et al*., 1999; Appendix 6).

Drilling and development of a well to completion is a costly investment (~ USD 12,000) of which many people do not afford in less developed countries like Tanzania (Kashaigili, 2010). Because of lack of groundwater quality information in a particular area one end up wasting money in drilling a well which eventually produces water of inferior quality mostly with high salinity levels. Salinity measurement in terms of electric conductivity (EC) can be used to delineate the occurrence and status of groundwater as it has been widely adopted as a convenient parameter for the first general characterization of groundwater quality. With few available boreholes data drilled across the country and previously published works, a general groundwater quality description is possible for informing prospective groundwater developer in Tanzania including Arusha where this study was conducted.

1.2 Statement of the problem

In Arusha city, groundwater is contributing more than 80% of the daily water production (~47 000 m^3) for domestic and other uses such as industrial and agriculture (AUWSA, 2014). Due to population increase the current water demand is about 93 000 m^3/d which is twice the amount supplied to the entire city by AUWSA. The situation has forced majority of the residents to carry out individual well drilling for commercial and domestic water supply purposes. Groundwater drilling and abstraction rates are not adequately regulated as a result of groundwater depletion in the study area. Some of depletion indicators include decline of water levels and subsequently yields reduction in wells that have been functioning for more than 20 years (Ong'or & Long-cang, 2007; GITEC & WEMA, 2011). Groundwater quality deterioration particularly increases in fluoride concentrations exceeding 10 mg/l which is beyond Tanzanian drinking water standards (1.5 mg/l) has been encountered in the wellfield (AUWSA personal communication, 2015). This is probably contributed partly by groundwater depletion whereby the effect can induce movement of water with inferior quality from adjacent aquifers. Therefore, the quality of groundwater used by population which is not served by AUWSA is uncertain. Also due to evidence of groundwater depletion, the status of groundwater quality in the entire wellfield is of utmost importance for proper groundwater management. Despite the ongoing intensive groundwater development, groundwater age and aquifer recharge mechanism of the wellfield has not been researched. Lack of such vital information hinders deliberation on informed planning and management decisions.

1.3 Rationale of the study

According to the well drilling reports from Arusha urban water supply and sanitation authority (AUWSA), groundwater abstraction in Arusha wellfield commenced in late 1960s. Currently, groundwater is contributing more than 80% of the daily water supply for domestic and other uses in Arusha city (AUWSA, 2014). However, groundwater development is not adequately controlled (Kashaigili, 2010; Van Camp *et al.*, 2014), even the amount of groundwater abstracted from the wellfield is not clear. For example in 2013 Pangani Basin Water Office (PBWO) carried out and inventory which revealed more than 400 wells in the wellfield were drilled without groundwater permit. Despite lack of reliable information on the extent of groundwater abstraction, there is evidence of groundwater depletion in the study area (Ong'or & Long-cang, 2007; GITEC & WEMA, 2011). The ongoing groundwater abstraction in the study area needs a thorough investigation to clearly document the current status of the wellfield and provide a better option for future groundwater management. Therefore, this study employed both field data and secondary data compiled from well drilling reports and monitoring records obtained from government agencies to assess groundwater abstraction trends and hydrogeochemical characteristics of Arusha wellfield for sustainable water resources utilization.

1.4 Objectives

1.4.1 General objective

The general objective of this study was to assess groundwater abstraction trends and hydrogeochemical characteristics of Arusha wellfield for sustainable water resources utilization

1.4.2 Specific objectives

(i) To assess hydrogeochemical characteristics and establish groundwater quality spatial variation in Arusha wellfield.

(ii) To assess groundwater abstraction and water level (drawdown) trends and possible impacts from existing production wells.

(iii) To establish groundwater age and recharge mechanism for sustainable groundwater utilization in Arusha City.

1.5 Research questions

(i) What are factors that influence groundwater chemistry and how does its quality varies in the wellfield?

(ii) To what extent do aquifers in Arusha wellfield have been depleted from the ongoing groundwater development?

(iii) What is the age of groundwater abstracted from Arusha wellfield and how does its abstraction affects sustainability of the aquifer?

1.6 Significance of the study

Groundwater management is a complex subject which needs accurate and reliable information including understanding of hydrogeological properties of an aquifer for informed decisions (Aeschbach-Hertig & Gleeson, 2012). Excessive groundwater abstraction which leads to depletion problem is becoming a global crisis and calls for better understanding of the aquifer dynamics (Wada *et al.*, 2010; Bakari *et al.*, 2012a; Famiglietti, 2014). Therefore, this study examines better options for evaluating and managing groundwater depletion in Arusha wellfield. It is expected that findings of this study are vital and may contribute to formulation of policies, bylaws and strategies for protection and management of the water resources in Arusha city. Groundwater abstraction trends, spatial variation of groundwater chemistry, age of groundwater and aquifer recharge mechanism are some of the findings from this study which are important and necessary for proper management strategy. Through information generated out of this study, the general public, water resources managers, policy makers and other stakeholders can equally benefit for future planning and management decisions. Additionally, the scientific findings of this study in most aspects establish the bases for future research works as well as any physical chemical changes in the aquifer systems.

1.7 Delineation of the study

Groundwater flow patterns modelling and groundwater balance in this study could be considered for further studies to ascertain how unregulated drilling affects the deep wells currently facing significant water level decline and subsequently discharge reduction. This study established water abstraction trends, hydrogeochemical characteristics and age of the groundwater in the wellfield but the interaction between adjacent aquifers and surface water bodies is not known.

CHAPTER TWO

GROUNDWATER SALINITY OCCURRENCE AND DISTRIBUTION IN TANZANIA

Abstract

Borehole data such as electric conductivity (EC), chloride, well depth, static water level (SWL), drawdown and yield were collected from government databases and reports for groundwater drilling projects all over the country. The data were analyzed using statistical techniques and ArcGIS software for establishment of saline groundwater distribution across Tanzania. Saline groundwater mapping revealed both brackish and freshwater in different parts of the country. The brackish water is commonly found in coastal areas with average value of conductivity ranging from 2271 to 5324 µS/cm. The elevated salinity level is mainly contributed by seawater intrusion as a result of intensive groundwater development along the coastal aquifers. The confined deep coastal aquifers ranging from 200 to 600 m below ground surface are characterized by relatively low concentration of conductivity, chloride and nitrate. This suggests that the effect of seawater intrusion is more pronounced in unconfined shallow aquifers. The northern and central Rift Valley region was observed to have fresh groundwater but with relatively high salinity level (1000-2000 µS/cm). The region falls within the East African Rift System (EARS) which is dominated by volcanic and sedimentary rocks. The origin and sources of high salinity levels are mainly weathering and mineral dissolution processes during water-rock interaction. In addition, trona is another factor which contributes to high salinity levels in groundwater due to leaching processes as a result of excessive evaporation commonly found in EARS. The western part of the country as well as southern highlands and Lake Victoria region were observed to have fresh groundwater with salinity levels less than 1000 µS/cm. The salinity level is relatively low and mainly influenced by local geology and in some cases may be contributed by anthropogenic activities such as irrigation water, fertilizer application and sewage effluents.

Key words: Saline groundwater, Electric conductivity, Tanzania

2.1 Introduction

Groundwater plays a fundamental role in human prosperous and a wide range of environmental services. It is the only source of water supply in arid region and supplementing water supply in semi arid and humid regions where surface water bodies are now becoming scarce and degraded because of the anthropogenic pollution and partly due to climate change effects. Thus, groundwater is widely accessible and less vulnerable to quality degradation than surface water bodies.

Fresh water supply is about 2.5% of the total global water resources and only less than 1% is available and accessible for human needs and ecosystems (Gleick, 1993; Shiklomanov, 1998). Large part of global water resources (~97.5%) is seawater with the remaining per cent distributed in ice caps and glaciers, groundwater, fresh lakes, soil moisture, atmosphere and rivers. Groundwater is however, classified based on total dissolved solids (TDS) as fresh water (0 – 1000 mg/l), brackish water (1000 – 10 000 mg/l), saline water (10 000 – 100 000 mg/l) and brine water (> 100 000 mg/l) (Van Weert *et al.*, 2009).

The occurrence of groundwater with different salinity levels is mainly governed by geological formations and mineralogical composition of the parent rocks. However, the quality of groundwater is not fixed in time rather it is subject to change. Some changes can be observed more quickly and others happen very slowly and are only significant at a geological time scale. Groundwater quality notably salinity levels may change in response to many factors both natural and anthropogenic influences. These include land use change due to human activities, groundwater pumping, intensive irrigation, fertilizer application, wastewater disposal, sea level rise as a result of climate change and meteorological processes such as evaporation and evapotranspiration.

According to Kashaigili (2010), the on-going groundwater resources development in Tanzania is being carried out without adequate knowledge of the resource in terms of quality and quantity due to lack of information and uncontrolled development. High costs of well drilling and development estimated to about USD 12 000 and hydrogeochemical analysis of about USD 20 per parameter (Kashaigili, 2010) have been a major constraint in groundwater development particularly when the aquifer under consideration is generally degraded because of either natural or anthropogenic drivers. It is therefore inevitable to establish baseline information based on the scattered available data on groundwater resources to avoid spending costs unnecessarily for already degraded or unsuitable aquifers prior embarking on actual development. One of the convenient ways in reaching the initial decision is to have knowledge of groundwater quality in terms of dissolved substances which are expressed in TDS (mg/l) or electrical conductivity, EC (µS/cm). This preliminary assessment informs the acceptability of groundwater prior to analysis of specific constituents based on the intended use. This gives an overview of the groundwater quality and leads to a decision whether to proceed with development or not. Whenever water quality is degraded may not be suitable for a particular use, but excess salinity levels are generally not suitable for many basic water uses. Saline groundwater may cause health problems, destroy fertile agricultural lands, increase costs of infrastructure maintenance and industrial processes as well as change or destruction of ecosystems.

Establishment of country groundwater salinity occurrence and distribution will inform water resources managers, policy makers and community at larger the current status and any future change of groundwater quality in terms of salinity levels across the country. This will also create a baseline for following up any phenomenal or scenarios such as climate change, overexploitation and land use change which are amongst the drivers likely to alter groundwater quality in different geological settings of the country. In this study, salinity measurements in terms of EC or TDS were used to delineate the occurrence and status of groundwater across the country as it has been widely adopted as a convenient parameter for a first general characterization of groundwater quality.

2.2 Location and climate of Tanzania

The United Republic of Tanzania is a nation in East Africa south of the equator. It lies between great lakes (Victoria, Tanganyika and Nyasa) and Indian Ocean. Tanzania shares its borders with Kenya and Uganda on the north; Indian Ocean, Comoro and Seychelles on the east; Mozambique, Malawi and Zambia on the south; and Democratic Republic of Congo, Burundi and Rwanda on the west (Fig.1). The country has a total area of 945 087 km^2 including 59 050 km^2 of inland water. Administratively, it has 31 regions (26 in Tanzania Mainland and 5 in Tanzania Zanzibar). According to the 2012 population and housing census, the population was 44 928 923 people with 97% of the population residing from Mainland and the 3% from Zanzibar (URT, 2013). The population projections for the year 2017 based on 2012 population and housing census was 51.5 million people (URT, 2016).

Generally Tanzania has a tropical climate but it varies greatly from tropical in coastal areas to temperate in the highlands and semi-arid in the central plateau (Basalirwa *et al.*, 1999). In the highlands, temperatures range between 10 and 20 °C during cold and hot seasons respectively. The rest of the country has temperatures rarely falling lower than 20 °C. The hottest period extends between November and February (25-31 °C) while the coldest period occurs between June and August (15-20 °C) (Basalirwa *et al.*, 1999). Tanzania has two major rainfall patterns: one is uni-modal (October-April) and the other is bi-modal (October-December and March-May) (Carpenter *et al.*, 1992; Zorita & Tilya, 2002; Foster & Chilton, 2003). The former is experienced in southern, central, and western parts of the country, and the latter is found in the north from Lake Victoria extending east to the coast. The bi-modal regime is caused by the seasonal migration of the Intertropical Convergence Zone (ITCZ) (Carpenter *et al.*, 1992). Annual rainfall is over 1500 mm on the northern highlands, to 1000 mm at the coast, down to 550 mm in the central plateau including Dodoma and Singida regions (Basalirwa *et al.*, 1999; Tenge *et al.*, 2004).

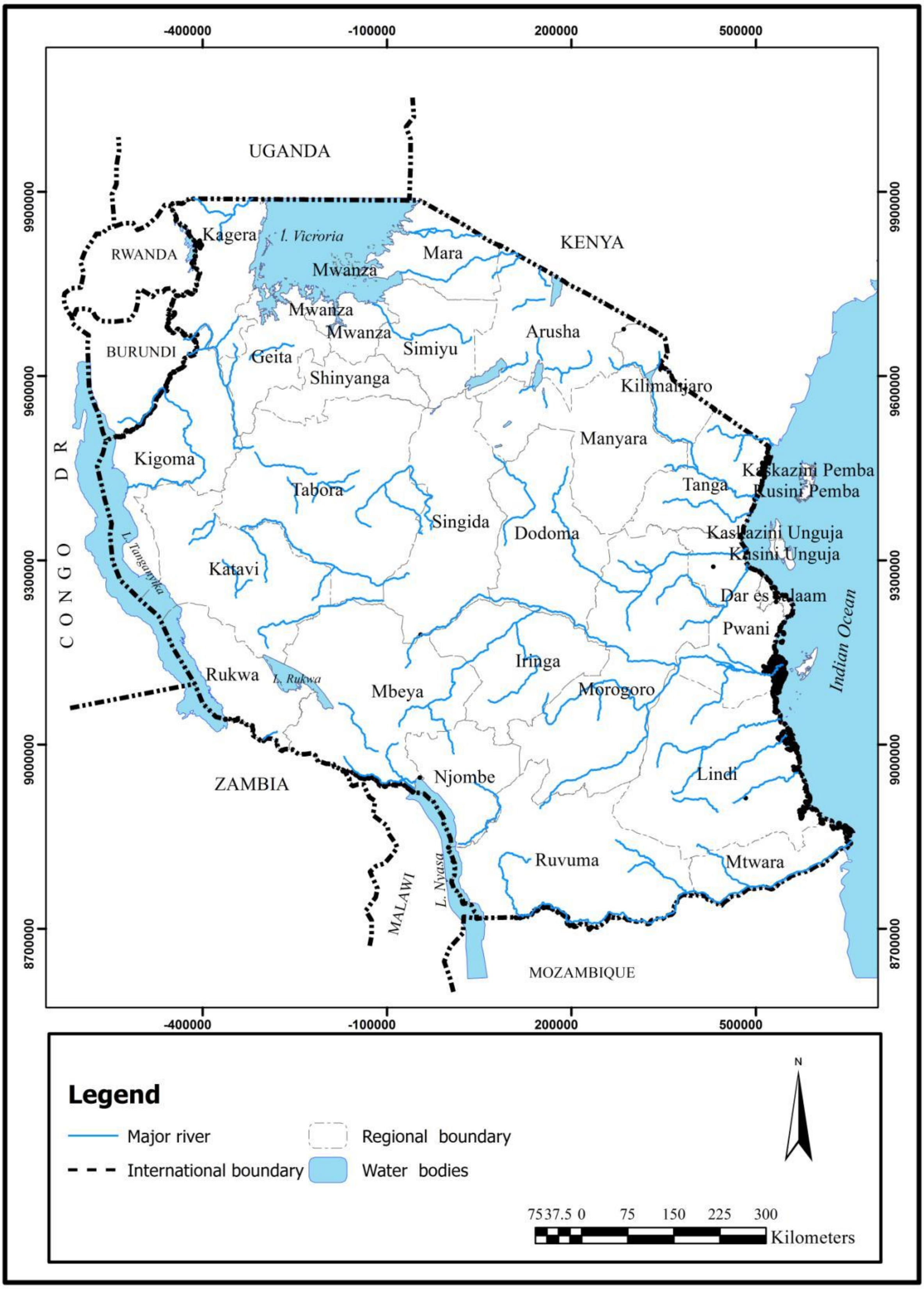

Figure 1: Tanzania map showing location, regional administrative boundary and major water bodies

2.3 Geology and hydrogeology

The geology of Tanzania is dominated by crystalline basement rocks formed during Precambrian. Generally, the Tanzanian geology started to form in the Precambrian, in the Archean and Proterozoic eons, and some cases are more than 2.5 billion years ago. Igneous and metamorphic crystalline basement rock forms the Archean Tanzania Craton, which is surrounded by the Proterozoic Ubendian belt, Mozambique Belt and Karagwe-Ankole Belt (Schlüter, 2008). Also Tanzania has experienced marine sedimentary rock deposition along the coast and rift formation inland, which has produced large rift lakes. The craton includes the vestiges of two Archean orogenic belts, the Dodoman Belt in central Tanzania, and the Nyanzian-Kavirondian in the north. The remains of these two belts produce lenses of sedimentary and volcanic rocks within granites and migmatite (Schlüter, 2008). The Dodoman Belt stretches for 480 km, broadening westward and is composed of banded quartzites, aplite, sericitic schist, pegmatite and ironstone. On the other hand, the Nyanzian Belt is mainly acid and basic basalt, dolerite, trachyte, rhyolite and tuff in separated zones south and east of Lake Victoria (Schlüter, 2008). The central plateau is composed of ancient crystalline basement rocks. These are predominantly faulted and fractured metamorphic rocks with some granite (Titus *et al.*, 2009). Groundwater flow is restricted to joints and fractures and is therefore limited. Groundwater is potentially more abundant in the topmost part of the basement which has been highly weathered in places and is hence friable and more permeable (Titus *et al.*, 2009).

The northern and southern highland regions are parts of the major East African Rift system which extends northwards through Kenya and Ethiopia, and which has developed over the last 30 million years through extreme crustal tension, rift faulting and volcanic activity. The Gregory Rift extends with a north-north-west trend through northern Tanzania and the Western Rift extends north-west to south-east along the south-western margin of Tanzania. The geology of the Rift zones comprises volcanic and intrusive rocks, largely of basaltic composition, but with some rare sodic alkaline rocks and igneous carbonates (e.g. Oldoinyo Lengai volcano). Some of the volcanic centres are active (producing new lava and ash formations periodically) (Roberts, 2002). The dominant hydrogeological features are the volcanic phonolitic and nephelinitic lavas, and sedimentary material of fine-grained alluvial and lacustrine origin. Groundwater is mainly available in both fractured or faulted formation and unconsolidated or semi-consolidated sediments (Ghiglieri *et al.*, 2010; Ghiglieri *et al.*, 2012).

The south-eastern part of the country is composed of sedimentary rocks of various ages (Palaeozoic to Recent), including the Karroo rocks and coal seams. The sediments are predominantly sandstones anticipated to be originated from an estuarine deltaic environment (Kent, 1971; Mpanda, 1997; Muhongo *et al.*, 2000). The sediments are mixed formations, including sandstones, mudstones and limestones. The coastal plain consists of largely unconsolidated sediments (beach sands, dunes and salt marsh) together with some limestone deposits (Nkotagu, 1989; Bakari *et al.*, 2012a). Potential groundwater reserve is hosted in the Quaternary deposits of Pleistocene to Recent periods which determine the geomorphology of the coastal plain (Walraevens *et al.*, 2015). Other parts of the country have not well studied and lack relevant and reliable hydrogeological information.

2.4 Origin of groundwater salinity

Electrical conductivity (EC) is a good measure of salinity as it reflects the total dissolved solid (TDS) in groundwater. Salinity in groundwater is contributed by various water constituents resulting from both natural and anthropogenic processes. Some factors (in particular anthropogenic) are only able to affect shallow aquifers while others are likely to reach even deeper ones. Generally, groundwater salinity is controlled by salt mineral dissolution in the aquifer matrix when water flows through subsurface environment.

Seawater intrusion occurs in coastal aquifers when fresh groundwater resources are abstracted for human or other use and when groundwater replenishment decreases the shallow fresh groundwater head will also decrease. This can cause up-coning of deeper saline groundwater and an inland movement of the seawater-groundwater interface.

When irrigated water is enriched with mineral salts and applied in excess to a crop land most likely will percolate to the shallow water table. Thus, the water vapour leaving the crops during this process is almost without dissolved solids, thus much less mineralized than the irrigation water supplied. Consequently, a residue of relatively mineralized water is left in the soil. From there it may adsorb to the soil matrix, drain to the surface water system or percolate below the root zone. In a way it may reach an aquifer and contribute to a progressive increase in salinity of its groundwater. Similarly, evaporation process especially in semi-arid or arid climate may affect shallow aquifers. This happens when climatic conditions favour evaporation (or evapotranspiration through plants) while flushing of accumulated salts is absent or only weak. Anthropogenic pollutants such as domestic and industrial effluents, residues from fertilizer applications may enter the groundwater system and contribute to increased salinity. Groundwater salinization effects of these processes will be rather localized.

2.5 Study approach

The information used in this study was collected from government databases and reports for groundwater drilling projects all over the country. The collected data for processing and interpretation included location name, electric conductivity (EC), well depth, static water level (SWL), drawdown and yield. In addition, previous published works on groundwater chemistry were compiled across the country though some regions lacked information because no studies have been carried out so far. The information compiled from literature made a significant contribution to this study especially interpretation of the salinity origin for different aquifers. Statistical analysis were performed for EC and other related parameters to infer its level of occurrence and distribution across the country. Finally the spatial distribution of salinity levels was plotted on the map of Tanzania using ArcGIS 10.3 software.

2.6 Results and discussion

Groundwater salinity mapping revealed both brackish and freshwater occurrence across the country (Table 1). In this study, four regions have been established based on salinity levels. These include, southern highlands and western region (< 500 µS/cm), Lake Victoria region (500-1000 µS/cm), Northern and central rift region (1000-2000 µS/cm) and coastal region (> 2000 µS/cm) (Table 2 and Fig. 2). The occurrence and distribution of groundwater salinity is mainly controlled by geology of the area and anthropogenic influence (Mjemah, 2007; Nkotagu, 1996a). However, the coastal areas (Tanga, Pwani, Dar es Salaam and Lindi) were observed to have generally brackish water (Fig.3) as a result of sea water influence (Mjemah, 2007; Van Camp *et al.*, 2014; Comte *et al.*, 2016).

Unlike geological influence, the human activities such as irrigation, manure and fertilizer application, domestic and industrial wastewater effluents mostly affect shallower aquifers (Mjemah, 2007). In coastal region where the seawater intrusion is expected to be high, anthropogenic contribution such as wastewater effluent seems to have negligible effect in terms of salinity input due to elevated level of chloride particularly in shallow aquifers (Fig. 4 and 5a).

Table 1: Statistical summary of borehole hydrogeological details and electric conductivity

SN	Region	Sample size	Depth (m)			SWL (m b.g.l.)			Yield (m^3/h)			EC (μS/cm)		
			Min.	Max.	Aver.	Min.	Max.	Aver.	Min.	Max.	Aver.	Min.	Max.	Aver.
1	Arusha	32	42	250	124	2.15	148.50	42.21	0.80	42.60	10.02	14	3330	1205
2	**Dar es Salaam**	**292**	**10**	**180**	**98**	**0.87**	**108.58**	**36.66**	**0.30**	**30.00**	**7.62**	**104**	**36000**	**3413**
3	Dodoma	41	55	212	125	0.65	119.70	31.70	0.40	27.00	8.49	548	7080	1796
4	Geita	8	70	130	109	1.19	25.49	7.63	1.05	6.24	3.48	201	1499	531
5	Iringa	20	26	160	89	1.00	49.27	14.50	0.88	100.00	10.67	161	7730	1177
6	Kagera	12	50	220	83	0.90	51.10	11.71	0.50	15.84	6.81	196	2430	1028
7	Katavi	18	100	110	104	2.00	12.95	6.79	0.81	14.00	4.00	199	2390	457
8	Kigoma	5	60	150	105	2.89	24.10	17.14	0.60	70.00	27.08			
9	Kilimanjaro	21	42	180	109	1.59	156.15	45.06	1.30	104.30	19.11	94	4835	1037
10	**Lindi**	**33**	**40**	**150**	**82**	**0.58**	**64.13**	**16.24**	**0.53**	**38.30**	**10.88**	**70**	**18410**	**2568**
11	Manyara	7	90	126	111	2.85	96.00	20.07	1.03	15.84	7.93	521	1640	1008
12	Mara	13	40	110	90	3.01	35.22	12.33	0.20	7.00	2.68	420	1454	831
13	Mbeya	26	35	120	63	1.97	43.50	14.44	0.15	22.30	5.53	102	1460	499
14	**Morogoro**	**50**	**5**	**150**	**84**	**2.05**	**41.14**	**13.34**	**0.40**	**30.71**	**8.25**	**425**	**7490**	**2271**
15	Mtwara	22	30	200	84	0.00	124.44	35.45	0.30	21.77	7.92	125	10000	1371
16	Mwanza	34	31.6	100	77	0.45	25.23	7.09	0.50	36.00	4.99	91	4970	989
17	Njombe	7	60	120	95	3.40	29.70	17.82	0.47	4.05	2.06	88	121	105
18	**Pwani**	**105**	**35**	**210**	**124**	**0.00**	**145.44**	**41.79**	**0.50**	**46.00**	**6.56**	**9**	**45900**	**3974**
19	Rukwa	6	50	76	64	1.57	13.76	8.85	0.63	24.00	7.41			
20	Ruvuma	5	54	91	69	8.67	44.15	18.74	0.70	4.40	2.04	120	954	340
21	Shinyanga	24	28	124	63	2.00	27.55	6.17	0.40	24.00	6.14	100	2800	1504
22	Singida	32	36	121	67	1.93	51.65	9.42	0.40	19.80	4.71	18	1770	334
23	Tabora	22	4.9	120	59	0.40	23.70	7.12	0.11	15.84	3.57	120	4040	947
24	**Tanga**	**27**	**28**	**145**	**91**	**0.25**	**60.66**	**12.58**	**1.09**	**42.00**	**13.95**	**526**	**31200**	**5324**
	Min		4.9	76	59	0.00	12.95	6.17	0.11	4.05	2.04	0.8	14	4
	Max		100	250	125	8.67	156.15	45.06	44.14	104.30	78.19	548	45900	5324
	Ave		42.6	148	90	1.77	63.42	18.95	2.39	35.13	11.09	184	9203	1477

Source: Data compiled from boreholes drilled across the country by Ministry of water and irrigation (2013-2016).

However, anthropogenic pollution has been evidenced by elevated levels of nitrate in shallow groundwater compared to deep ones (Bakari *et al*., 2012a; Fig. 5b). The predominance of brackish water with average conductivity ranging from 2271 to 5324 µS/cm indicates that seawater has laterally intruded fresh groundwater along the coastal region (Figs. 2 and 3). This may be due to reduced groundwater replenishment as a result of land use and land cover change. Apart from reduced recharge, coastal area of Tanzania like many other parts of the world is dominated by large cities including Dar es Salaam and Tanga which implies large amount of groundwater withdraws (Van Camp *et al.*, 2014). The main water types in the coastal area include Na-Cl and NaCa-HCO_3 (Mjemah, 2007; Bakari *et al*., 2012a; Mtoni *et al*., 2013). Groundwater abstraction induces inland seawater movement and when mixed with fresh groundwater the salinity level increases significantly. However, confined deep coastal aquifers ranging from 100 to 600 m below ground surface were observed to have relatively low levels of conductivity, chloride and nitrate (Fig. 5). This suggests that the effect of seawater intrusion is more pronounced in unconfined shallow aquifers which have undergone intensive development in most coastal areas of Tanzania (Mtoni *et al.*, 2013; Van Camp *et al.*, 2014).

Table 2: Classification of groundwater salinity in Tanzania

Region	Average EC (µS/cm)	Remark
Katavi, Njombe, Ruvuma, Mbeya, Singida	< 500	Fresh water
Geita, Mara, Mwanza, Tabora, Shinyanga	500-1000	Fresh water
Arusha, Dodoma, Iringa, Kagera, Kilimanjaro, Manyara, Mtwara	1000-2000	Fresh water
Dar es Salaam, Lindi, Morogoro, Pwani, Tanga	>2000	Brackish water*

*Brackish water is water that has more salt than freshwater, but not as much as seawater. It may result from mixing of seawater with freshwater (occurs in brackish fossil aquifers).

Generally, groundwater in coastal region is classified as brackish water. However, Mtwara which is in southeast coast of Tanzania (Fig. 2) was observed to have fresh groundwater with average conductivity of 1371 µS/cm at average well depth of 84 m. The level of salinity in groundwater of this area is far below compared to the rest of groundwater encountered along the coastal aquifers where the maximum salinity was observed in Tanga (5324 µS/cm) northeast of the country. A consistence decrease of salinity levels was observed as one move from northeast to southeast along the Indian Ocean. Probably this may be explained by underlying geological formation which is not covered in this study.

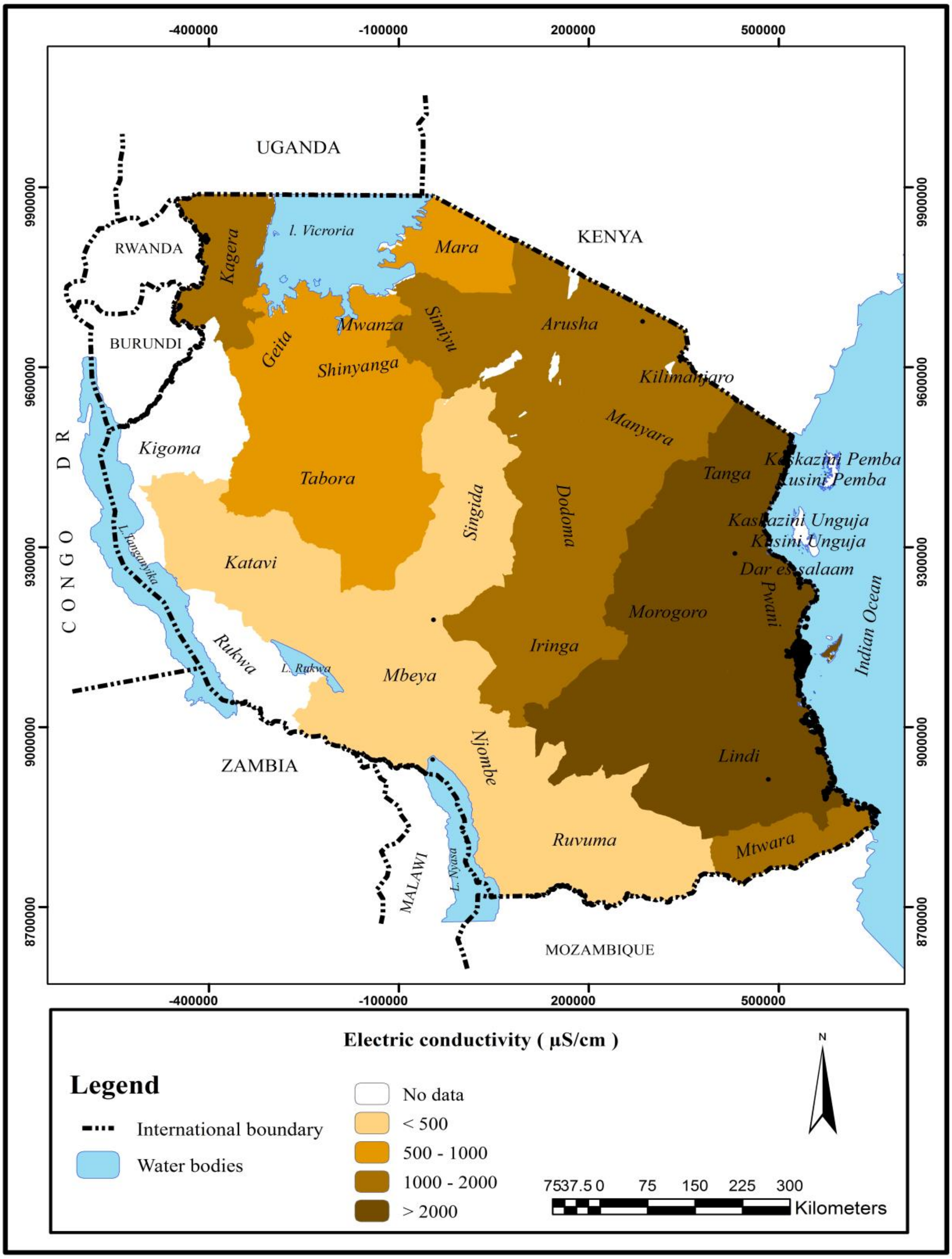

Figure 2: Saline groundwater occurrence and distribution in Tanzanian (source: data compliled from boreholes drilled across the country by Ministry of water and irrigation, 2013-2016)

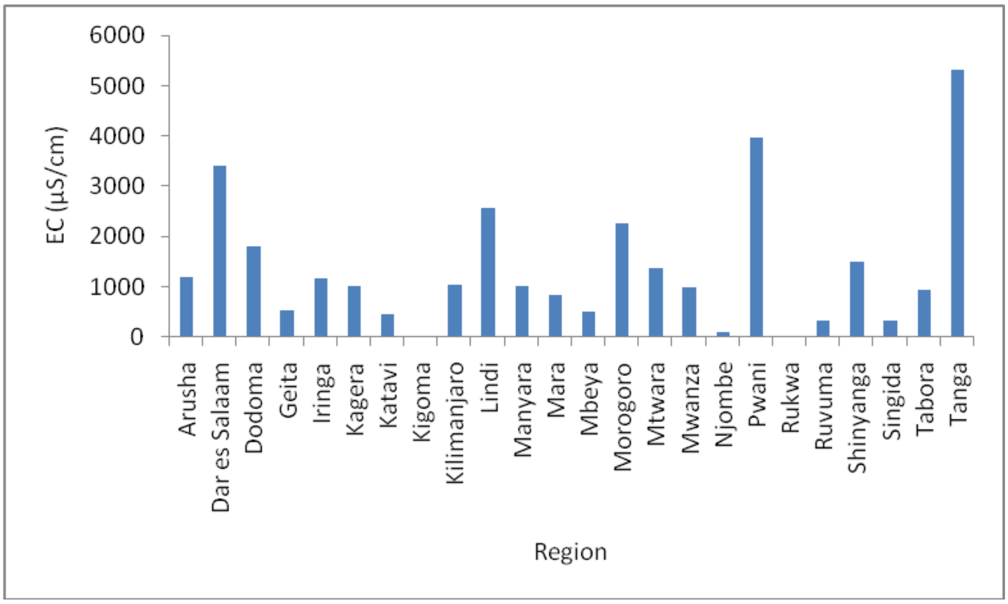

Figure 3: Electric conductivity distribution in Tanzanian groundwater (Source: Data compliled from boreholes drilled across the country by Ministry of water and irrigation, 2013-2016)

The west region including southern highlands (< 500 µS/cm) and Lake Victoria region (500-1000 µS/cm) were observed to have fresh groundwater with varying salinity levels up to 1000 µS/cm (Fig. 2). The regions lie alongside great lakes (Victoria, Tanganyika and Nyasa) both with fresh water. The salinity level is relatively low and mainly influenced by local geology and in some cases may be contributed by anthropogenic activities such as irrigation water, fertilizer application and sewage effluents. The origin of groundwater salinity in this region is mainly due to dissolution of minerals from Precambrian crystalline basement rocks which include granites, gneisses, quartzite, and migmatites. Generally, fresh groundwater with conductivity ranging from 200 to 1200 µS/cm has been encountered in central part of the country particularly Tabora extending towards Lake Victoria (Davies & Dochartaigh, 2002). The reported average conductivity (700 µS/cm) in Tabora region agrees with values presented in Table 1. The dominant water type in the region includes Na-Cl and NaCa-HCO_3 (Davies & Dochartaigh, 2002).

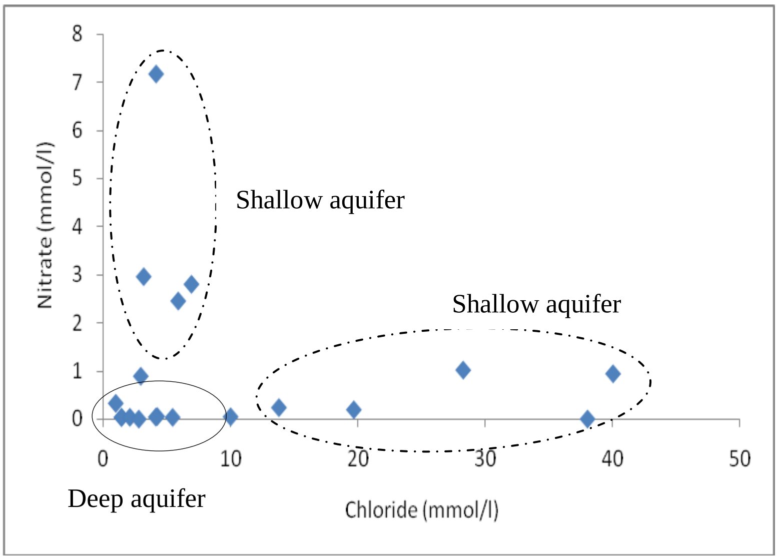

Figure 4: Concentrations of chloride and nitrate in shallow and deep Tanzanian coastal aquifers (Bakari *et al*., 2012a)

Table 3: Groundwater conductivities reported in different parts of Tanzania

Region	Sample size	EC (µS/cm)	Average depth (m)	Reference
Dodoma	29	927	48	(Shindo, 1989)
Dodoma	22	907		(Rwebugisa, 2008)
Tabora	28	945		(Davies & Dochartaigh, 2002)
Singida	17	850		(Titus *et al*., 2009)
Dar es Salaam	23	1663	38	(Mato, 2002)
Dar es Salaam	6	1061	404	(Bakari *et al*., 2012b)
Dar es Salaam	13	2029	64	(Bakari *et al*., 2012b)
Dar es Salaam	49	1777	36	(Walraevens *et al*., 2015)

The northern and central Rift Valley regions were observed to have fresh groundwater but with relatively high salinity level (1000-2000 µS/cm). The region is dominated by volcanic rocks in the north and crystalline basement rocks in the central part which extends to Singida and Dodoma. Groundwater is hosted in fractured and weathered formations dominated by relatively high salinity levels (Nkotagu, 1996a; Bretzler *et al*., 2011; Ghiglieri *et al*., 2012) as a result of weathering and mineral dissolution during water-rock interaction. This is also evidenced by high Na^+ and low Ca^{2+} ions in groundwater encountered in the region (Bretzler *et al*., 2011) which implies long mean residence time. The levels of groundwater salinity in this region extend to some areas of Lake Victoria region (Fig. 2). In some cases, high salinity levels in groundwater is reported to have been a result of excessive irrigation activity (Northey *et al*., 2006; Batakanwa *et al*., 2013) though it is limited in shallow aquifers.

In volcanic region within the East African Rift System, trona (evaporite mineral) dissolution is another factor which contribute to high salinity levels in groundwater due to evaporation and leaching processes (Kaseva, 2006; Pittalis, 2010). Trona is more abundant in dark soil and commonly found few meters below ground surface. It is also common and found at very high levels in the East African Rift system saline lakes such as Turkana, Suguta, Baringo, Natron and Manyara (Olaka *et al.*, 2010) all these contribute to high salinity levels in groundwater of this region (Apaydin, 2010; Arslan *et al.*, 2015). High salinity levels in shallow aquifers in areas dominated by trona has been reported in central part of Tanzania (Fig. 6) where dugouts and shallow wells of up to 10 m deep were observed to have high levels of conductivity, chloride and sodium ions than deep wells (~90 m) (Titus *et al.*, 2009).

Groundwater salinity occurrence and distribution may significantly differ within a small area depending on the subsurface local geology. For example, some wells along the coastal aquifers were observed to have fresh groundwater (Table 1) despite the region being classified under saline or brackish water. Similarly, Table 3 shows previous works which indicate occurrence of some fresh groundwater in Dar es Salaam coastal aquifers.

Therefore, this study becomes the first step toward delineation of groundwater salinity distribution in Tanzania but more details are necessary for specific groundwater development cases in a particular region. In view of the aforementioned scenarios together with the ongoing intensive groundwater development in Arusha city (Ong'or & Long-cang, 2007; GITEC & WEMA, 2011) a more detailed investigation on groundwater hydrogeochemistry was carried out and the results are reported in the next chapter.

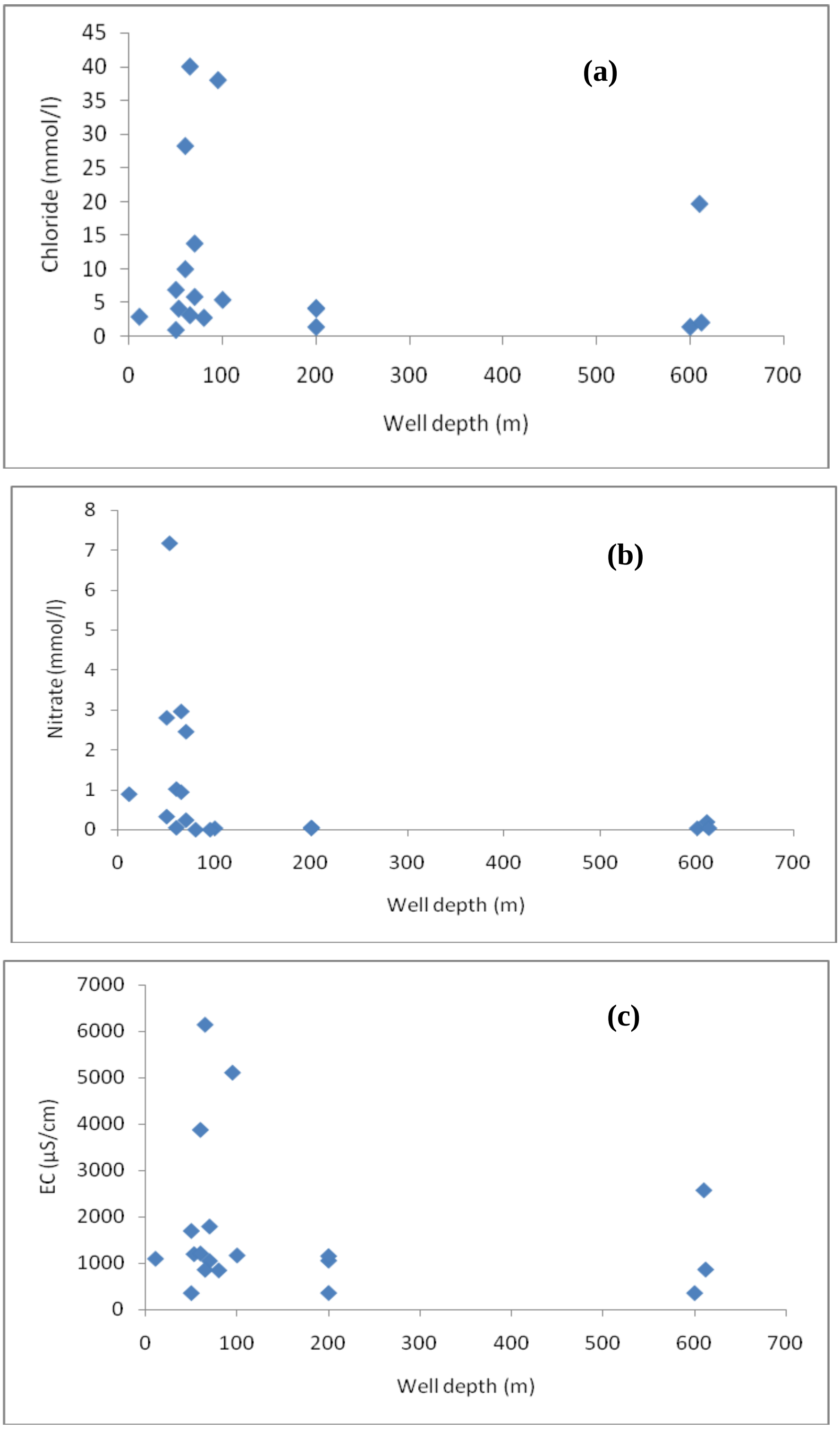

Figure 5: Groundwater salinity variation with depth in coastal aquifers (a) chloride (b) nitrate (c) condcuctivity (Bakari *et al*., 2012a)

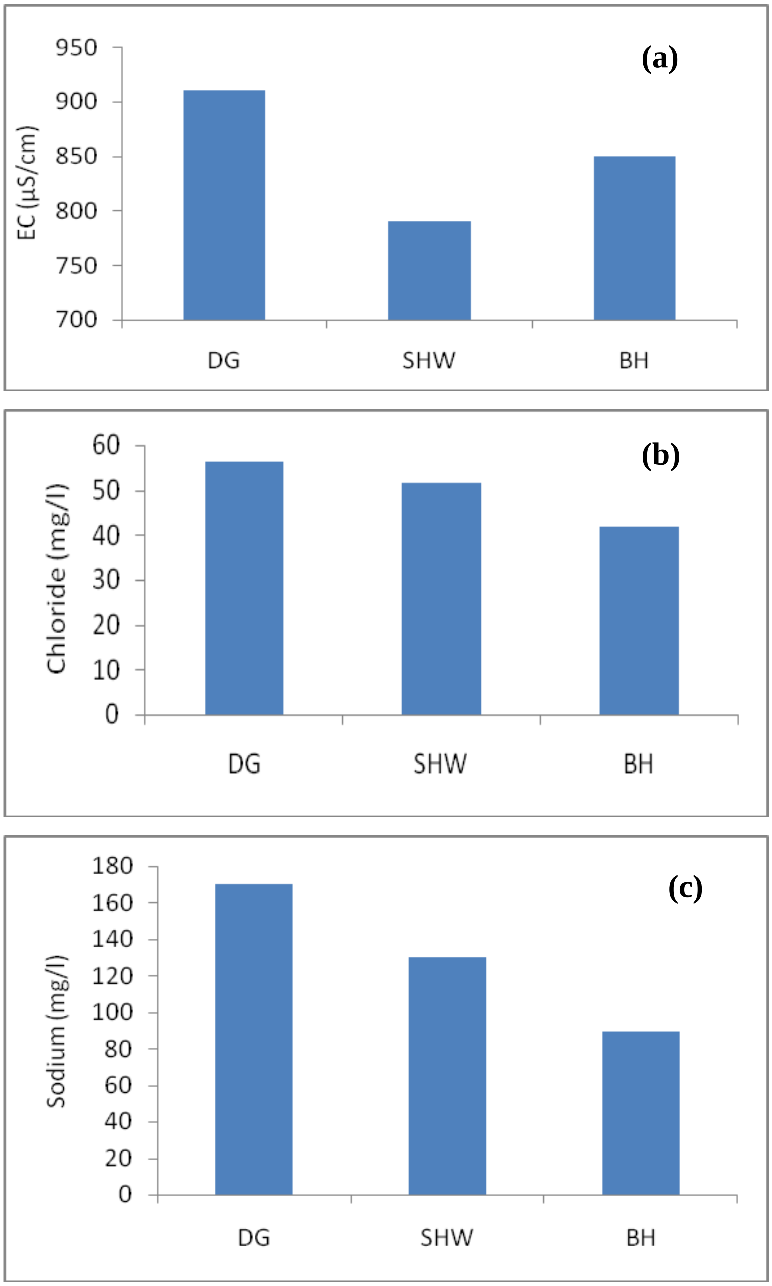

Figure 6: Effect of trona dissolution in groundwater salinity in central Tanzania (a) conductivity (b) chloride (c) sodium (Titus *et al*., 2009)

2.7 Summary and conclusions

Mapping of saline groundwater in Tanzania revealed both brackish and freshwater in different parts of the country. The brackish water is commonly found in coastal areas from Tanga in the north to Lindi in southeast. The salinity level in terms of average conductivity ranged from 2271 to 5324 µS/cm (Table 1). Apart from mineral dissolution, elevated salinity level is contributed by seawater intrusion as a result of intensive groundwater development along the coastal aquifers in which major towns and cities are located. Contribution of anthropogenic activities is also noticeable but becomes negligible because of high salinity levels from seawater intrusion. However, confined deep coastal aquifers ranging from 100 to 600 m below ground surface were observed to have relatively low levels of conductivity, chloride and nitrate compared to semi-confined and unconfined ones (Bakari *et al*., 2012a, 2012b). This suggests that the effect of seawater intrusion is more pronounced in unconfined shallow aquifers which have undergone intensive groundwater development in most coastal areas of Tanzania.

The northern and central Rift Valley region was observed to have fresh groundwater but with relatively high salinity level (1000-2000 µS/cm). The region falls within the East African Rift System (EARS) which is dominated by volcanic and sedimentary rocks. The origin and sources of high salinity levels are mainly weathering and mineral dissolution processes during water-rock interaction. This is also evidenced by high Na^+ and low Ca^{2+} ions in groundwater encountered in the region. However, the broader spectrum of groundwater hydrogeochemistry of Arusha city (study area of this work) is discussed under chapter three (3) of this report. In addition, trona which is an evaporite mineral in the EARS is another factor which contributes to high salinity levels in groundwater due to evaporation and leaching processes.

The west part of the country including southern highlands and Lake Victoria region was observed to have fresh groundwater with salinity levels less than 1000 µS/cm. The salinity level is relatively low and mainly influenced by local geology and in some cases may be contributed by anthropogenic activities such as irrigation water, fertilizer application and sewage effluents. Apart from anthropogenic influence, the origin of groundwater salinity in this region is due to dissolution of minerals from basement rocks which include granites, gneisses, quartzite, and migmatites.

CHAPTER THREE

HYDROGEOCHEMICAL CHARACTERISTICS AND SPATIAL DISTRIBUTION OF GROUNDWATER QUALITY IN ARUSHA WELL FIELDS, NORTHERN TANZANIA[1]

Abstract

Arusha aquifers have been exploited intensively serving as the main source of domestic water supply in the city. But the quality of groundwater is not clearly documented for future planning and management. Hydrogeochemical assessment was carried out to establish groundwater quality and its spatial distribution with the aid of geostatistical techniques. Groundwater samples were collected and analyzed for major cations and anions using conventional methods of water analysis. Well lithology and geological map were considered for hydrogeological interpretation of the area. The results of piper diagram revealed Na-K-HCO_3 water type with sodium and bicarbonate ions dominating in all samples. High fluoride concentrations and general groundwater chemistry are mainly controlled by aquifer lithology than anthropogenic activities. The levels of anthropogenic pollution indicators such as nitrate, chloride and sulphate in deep wells are generally low and most likely coming from natural sources. The geological sections indicate two potential aquifers (volcanic sediment and weathered/fractured formation) both yield water containing significant concentration of fluoride. Eighty two (82) percent of the analyzed groundwater samples indicated fluoride concentrations higher than WHO guidelines and Tanzanian drinking water standards (1.5 mg/l). The southern part of the study area yields groundwater of better quality for human consumption than northern zones which is at high elevation on the foot of Mt. Meru. With exception of fluoride the quality of groundwater in the study area is generally suitable for drinking purpose and other socioeconomic uses.

Key words: Groundwater quality; Hydrogeochemical; Arusha

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3.1 Introduction

Water is the most important natural resource for continued existence of any community or ecosystem (Jha *et al.*, 2007; Kløve *et al.*, 2014; Gleeson *et al.*, 2016). Most social economic processes and functions of a particular community are largely depending on potable water supply (Brown & Lall, 2006; Chenoweth, 2008; Komakech *et al.*, 2012). Its vital role necessitates the importance of understanding water resources dynamics throughout the world for present and future use (Schmoll *et al*., 2006; Heathwaite, 2010; Hellar-Kihampa *et al.*, 2013). Due to socio-economic development, rapid population growth and increased incidences of freshwater pollution (Schwarzenbach *et al.*, 2010), groundwater exploitation has increased tremendously in many parts of the world (Taylor *et al.*, 2013; Venetsanou *et al.*, 2015; Cheema, 2016). Knowledge on the availability and quality of water is inevitable in groundwater development and management programs.

The quality of groundwater is mainly governed by local geology and highly influenced by environmental factors (Fitts, 2002). Factors such as rainfall, temperature and pH conditions facilitate different subsurface physical chemical processes such as weathering, dissolution and ion exchange (Gizaw, 1996). Under ideal conditions, these processes are the ones that determine groundwater chemistry and its quality as it moves across different geological formations (Kump *et al.*, 2000; Olobaniyi & Owoyemi, 2006). However, apart from natural and anthropogenic pollution sources, over-abstraction has been reported worldwide as a threat to both groundwater quality and quantity (Changming *et al.*, 2001; Delinom, 2008; Wada *et al.*, 2010). In order groundwater abstraction to be sustainable, a better understanding of both quantity and quality of water need to be defined by applying proper management strategies with the aid of reliable hydrogeological and hydrogeochemical data of an aquifer (Gleeson *et al.*, 2012). This study focused on geostatistical methods for establishing groundwater quality spatial distribution in the study area. The use of Geographic information system (GIS) technique has been widely adopted in proper planning and management of groundwater resource (Dixon, 2005; Jha *et al.*, 2007; Rahmati *et al.*, 2015) due to its vast capability of effective storage, spatial analysis, and presentation of graphical outputs on water quality issues (Fenta *et al.*, 2015; Venkatramanan *et al.*, 2015). Hydrogeochemical data and spatial analysis helps to understand the groundwater quality distribution and its suitability based on available local standards and World health organization’s (WHO) guidelines for various uses. Such knowledge helps water resource managers and policy makers to properly plan and manage the vital resource for present and future use.

The current study was conducted in a volcanic area (southern slope of Mt. Meru) located within East African Rift System. The quality of groundwater in the rift system has been reported in previous works particularly in the Main Ethiopian Rift whereby high levels of fluoride, bicarbonate and sodium are a major concern due to high rate of carbon dioxide outgassing, acid volcanic and geothermal heating (Gizaw, 1996; Bretzler *et al*., 2011). High fluoride level in drinking water is a serious threat to human health specifically causing dental fluorosis and other related diseases (Moturi *et al.*, 2002). Such natural contaminants are not uniform in groundwater systems rather are distributed depending on geological formation of a particular aquifer. This necessitates the need of undertaking hydrogeochemical investigations to determine the quality of water intended for public supplies by ensuring compliance with local and international standards. Ghiglieri *et al*. (2012) conducted hydrogeological and hydrochemistry study on the northeastern part of Mt. Meru in Arusha Tanzania where fluoride levels of up to 68 mg/l was observed in alkaline volcanic zones. The northern slopes of Mt. Meru is relatively dry (leeward side) compared to southern part of the mountain where the current study was carried out.

In the City of Arusha, which is situated in southern slopes of Mt. Meru, Northern Tanzania, the main sources of water supply is groundwater (Mbonile, 2005). The contribution of surface water (rivers) to the total amount of water abstracted is high only during rainy season. This implies that the city depends largely on groundwater as the main source of water supply for socio-economic development. According to Arusha Urban Water Supply and Sanitation Authority (AUWSA) medium term strategic plan (2015-2020) report, groundwater contributes more than 80% of the daily water production (~47 000 m^3) supplied to the city (AUWSA, 2014) with a population of about 739 640 inhabitants in accordance with 2012 population and housing census (URT, 2013). The population increase accelerates rapid growth and expansion of the city and more demand on services including potable water supply (current water demand is 93 000 m^3/d) which forces water authority to prolong water pumping from the aquifers.

Nevertheless, most deep wells in the study area were drilled and have been continuously operating for more than three decades. Previous works have noted decrease in both boreholes' yields and subsequently water levels decline in the area (Ong'or & Long-cang, 2007; Kashaigili, 2010; GITEC & WEMA, 2011). This is attributed to rapid urbanization, industrial growth and expansion of irrigated agriculture in the area which has escalated the water supply demands (Noel *et al*., 2015). The problem of over-abstraction of groundwater resource has been and will keep increasing as a result of uncontrolled groundwater development in the city and all over the country (Custodio, 2002; Reddy, 2005). Furthermore, according to AUWSA personal communication (2015), several boreholes have been abandoned due to increase in fluoride concentrations exceeding 10 mg/l which is beyond Tanzanian drinking water standards (1.5 mg/l). Despite all these challenges, baseline and monitoring information on the trends of groundwater quality in the respective aquifers are lacking. However, pumping has been done continuously without proper understanding of the quality changes in different hydrogeological settings of the area.

Therefore, this study aimed at assessing hydrogeochemical characteristics and establishing spatial variation of groundwater quality in the City of Arusha for future groundwater management plans. The study used existing wells and springs for generating the needed information. All major cations and anions including fluoride were analyzed using conventional methods of water analysis and the results were compared with both available local standards, Tanzania bureau of standards (TBS) and World health organization's (WHO) guidelines.

3.2 Study area

3.2.1 Location

The study was conducted in Arusha City and Arusha District, located on the southern slopes of Mount Meru in Northern Tanzania. The study area is bordered by three administrative districts of Monduli, Longido, and Meru (Fig. 7). The area covers an area of 282 km^2 and lies between latitudes 3° 15' and 3° 30' South and longitudes 36° 34' and 36° 46' East (Fig. 7). According to the 2012 population and housing census, the Arusha city and Arusha District had a population of 416 442 and 323 198 inhabitants respectively (URT, 2013).

3.2.2 Climatic characteristics

The area is characterized by tropical climate with two distinct seasons, dry and wet seasons. The rainfall pattern in Arusha as part of northern Tanzania is bimodal with short rains from October to December and long rains from March to May (Fig. 8) (Zorita & Tilya, 2002; Kijazi & Reason, 2009). The annual total rainfall ranges between 500 mm and 1200 mm with mean value of about 842 mm (Kaihura *et al*., 2001). The temperature typically ranges between 13°C and 30°C with an average annual temperature of about 25°C. The coolest month is July whereas the warmest is February. The relative humidity varies from 55 to 75% (Anderson *et al*., 2012) and annual potential evapotranspiration of 924 mm (GITEC & WEMA, 2011).

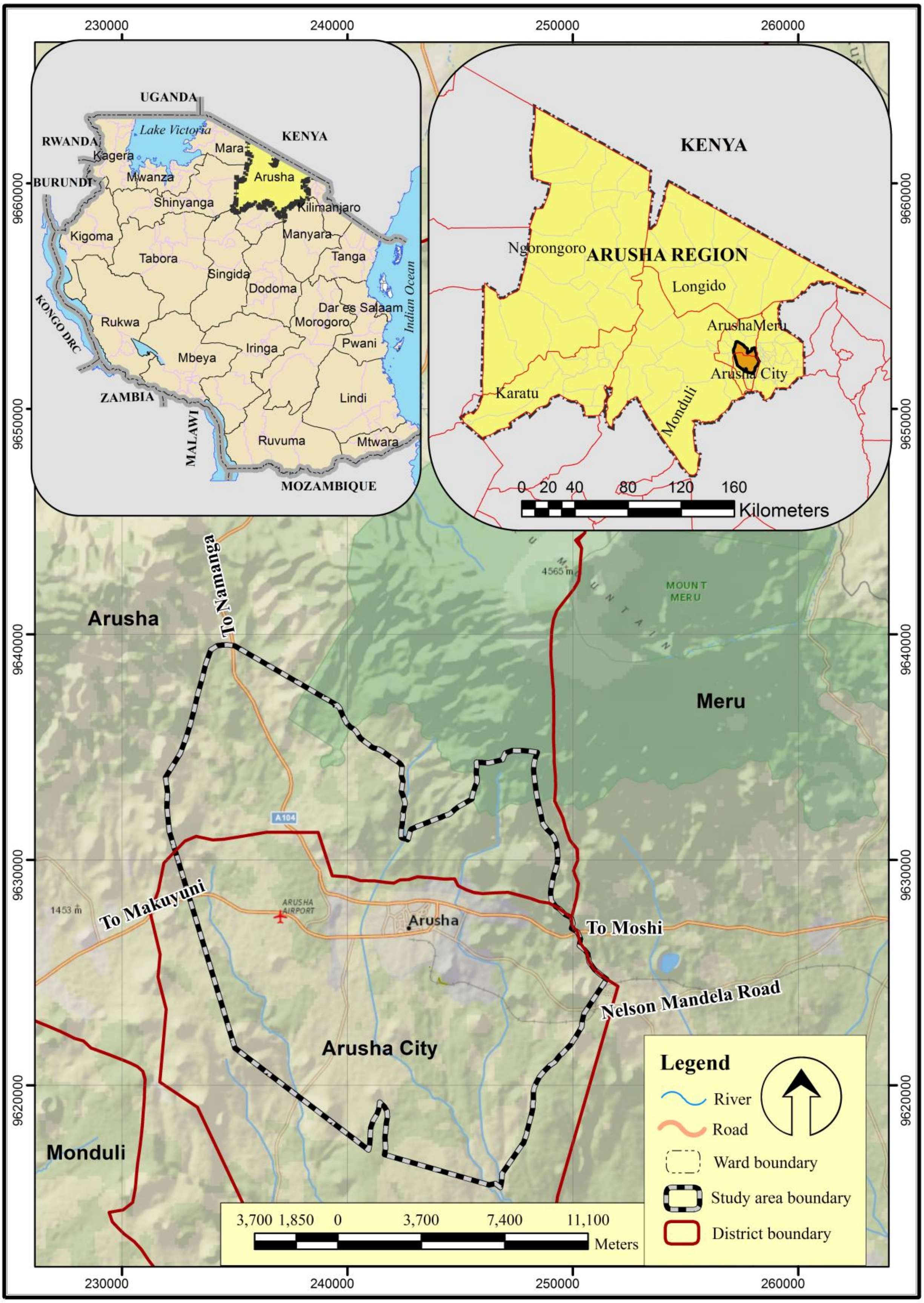

Figure 7: Location of the study area

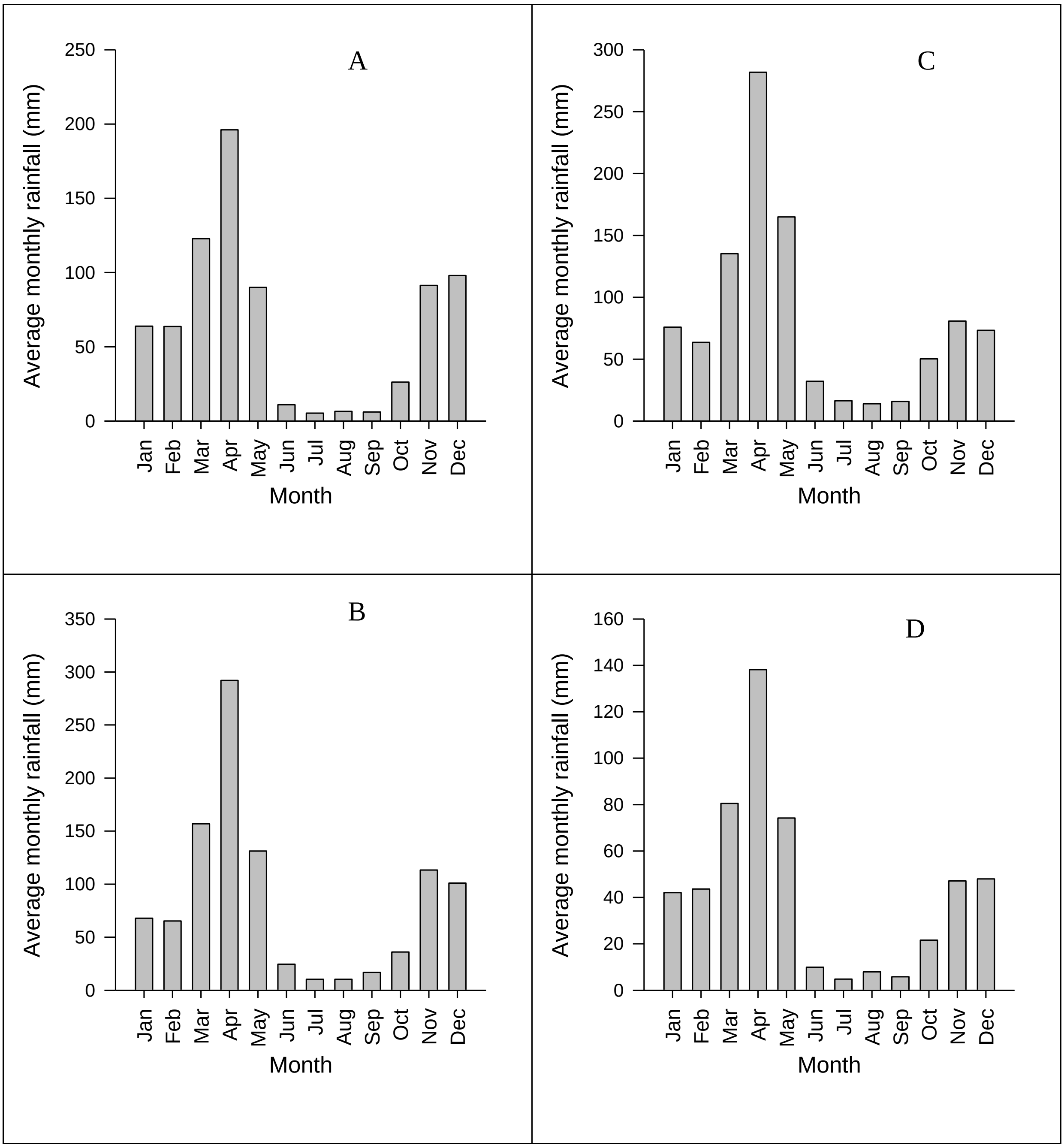

Figure 8: Bimodal rainfall pattern in Northern Tanzania. A, B, C and D represent Arusha Airport, Arusha Maji, Tengeru and Kilimanjaro International Airport MET stations respectively (TMA, 2013)

3.2.3 Geological and hydrogeological settings

The geology of the study area is dominated by volcanic materials of varying ages and recently deposited alluvial sediments (Wilkinson *et al.*, 1986; Ong'or & Long-cang, 2007; Ghiglieri *et al.*, 2008; Ghiglieri *et al.*, 2010). Mt. Meru is the main center of volcanic activities in the region. The main features of the volcanic eruption in the area include main cone deposits, mantling ash, lahars, lava flows, pyroclastic materials, tuffs, pumice, agglomerates and volcanic rocks such basalts (Nanyaro *et al.*, 1984; Ong'or & Long-cang, 2007). Some of these volcanic features have been depicted in hydrogeologic map (Fig. 9) together with the cross section derived from hydrogeological map running from the steep slopes of Mt. Meru towards the foot of the Mountain (Fig. 10). Volcanic rocks are mainly lava flows (basaltic to phonolitic and nephelinitic tuff). These materials, if not fractured or weathered they act as aquitard which favor groundwater movement down the slope (Flint *et al.*, 2001; Wilson & Guan, 2004). The properties of these geological formations normally change with time due to various physical chemical reactions such as weathering and subsequent volcanic and tectonic activities. Mount Meru region is dominated by volcanic and sedimentary hydrogeologic formations with various mineralogy compositions. These include fluorapatite, natrite, halite, sylvite, aphthitalite, calcite, goethite, phillipsite, chabazite, augite, sanidine, analcime, leucite, nepheline, anorthoclase, biotite, cancrinite, riebeckite, albite and illite (Ghiglieri *et al.*, 2012)

The area is also affected by tectonism leading to the development of fractures and faults which act as conduit to groundwater flows in some areas (Ghiglieri *et al.*, 2010). Figure 9 shows the fault system within the main cone deposits of pyroclastic materials with subordinate nephelinitic and phonolitic lavas. The fault lines are assumed to be avenue of huge groundwater flows that manifest through numerous springs which discharge into Themi River. Volcanic sediments and alluvium derived from different volcanic materials such as ashes, pyroclastic materials, weathered and fractured volcanic formation (e.g., basalts), phonolitic to nephelinitic formation form the major potential aquifers in the study area (Ghiglieri *et al.*, 2010). However, mantling ash, volcanic ash and tuff, and sedimentary formations particularly fine grained alluvial sediments are characterized by low transmissivity which become practically impermeable. In most cases such hydrogeological units act as aquitard or low yield aquifers. Groundwater recharge is mainly taking place in high elevation on the slopes of Mt. Meru along fractured formations as well as through infiltration in valleys or depression zones with medium to coarse grain sizes (Ghiglieri *et al.*, 2010). Groundwater potentiality in fractured formation is also supported by a number of springs around the fault zone (Fig. 9), northeastern side of the study area. Springs' flows from this zone are very high particularly after or at the end of long rains. For example in May 2015 a total of 25 698 m^3/d was abstracted from the springs by AUWSA for public water supply. This amount is only the portion of groundwater discharged from springs along this fault, the remaining water flows into Themi River which is one among the perennial and reliable water sources in the study area. Overall, most rivers and streams originate from springs located on the slopes of Mt. Meru particularly in fractured formations at high elevations. Major rivers include Themi, Kijenge, Ngarenaro, Burka and Engare Olmotonyi (Fig. 9)

Based on the hydraulic head observed from existing production wells groundwater flows from north to south direction towards the foot of Mt. Meru. This is well supported by wells W12 and W17 with hydraulic heads at 1356 and 1348 m a.s.l. respectively. Thus groundwater flows from W12 with high hydraulic head also located at elevated area to W17 with hydraulic head difference of 8 m at a distance of 1.2 km. Figure 11 shows potential aquifers as derived from well logs data in the study area (Appendix 3). The W12, W15, W16 and W9 are among the existing production wells in the area. W19 taps water from weathered or fractured basalt aquifer whereas, the rest collect water from either formation depending on the arrangement of hydrogeological units and position of the screens. This indicates that groundwater occurs both in fractured formation and volcanic sediment hosted aquifers. As mentioned before, fractured formations seem to be more productive aquifers as well as potential recharge zones in the area. Though volcanic sediment hosted aquifers cannot be ignored as they also produce substantial amount of water in the area. A good example of the well tapping water from volcanic sediment formation is W12 which discharge up to 192 m^3/h. However, more information are needed to delineate the aquifer geometry as most wells used in this study lack hydrogeological data including well logs, depth and specific yield.

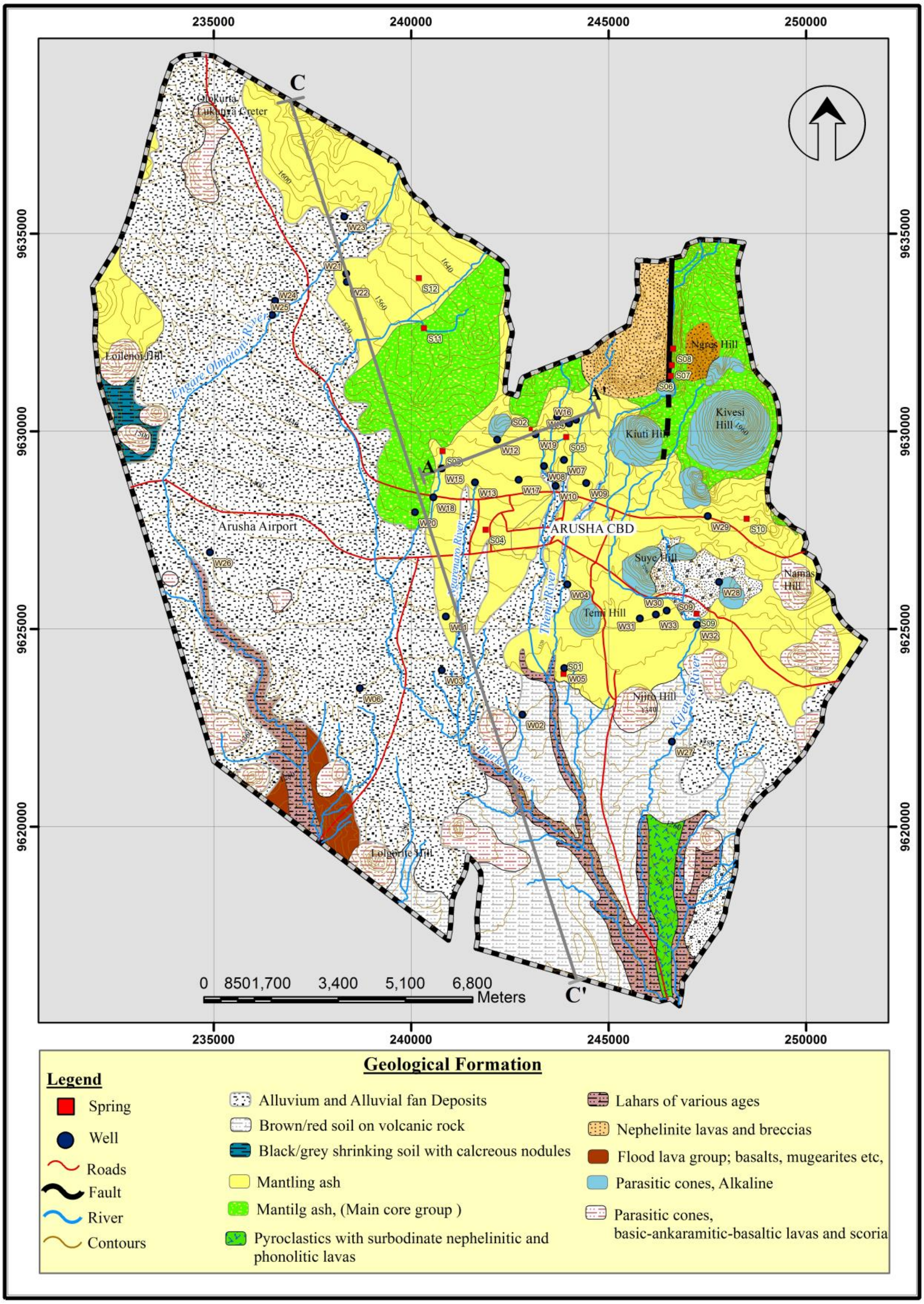

Figure 9: Hydrogeological map showing location of sampling sites (AA.VV., 1983)

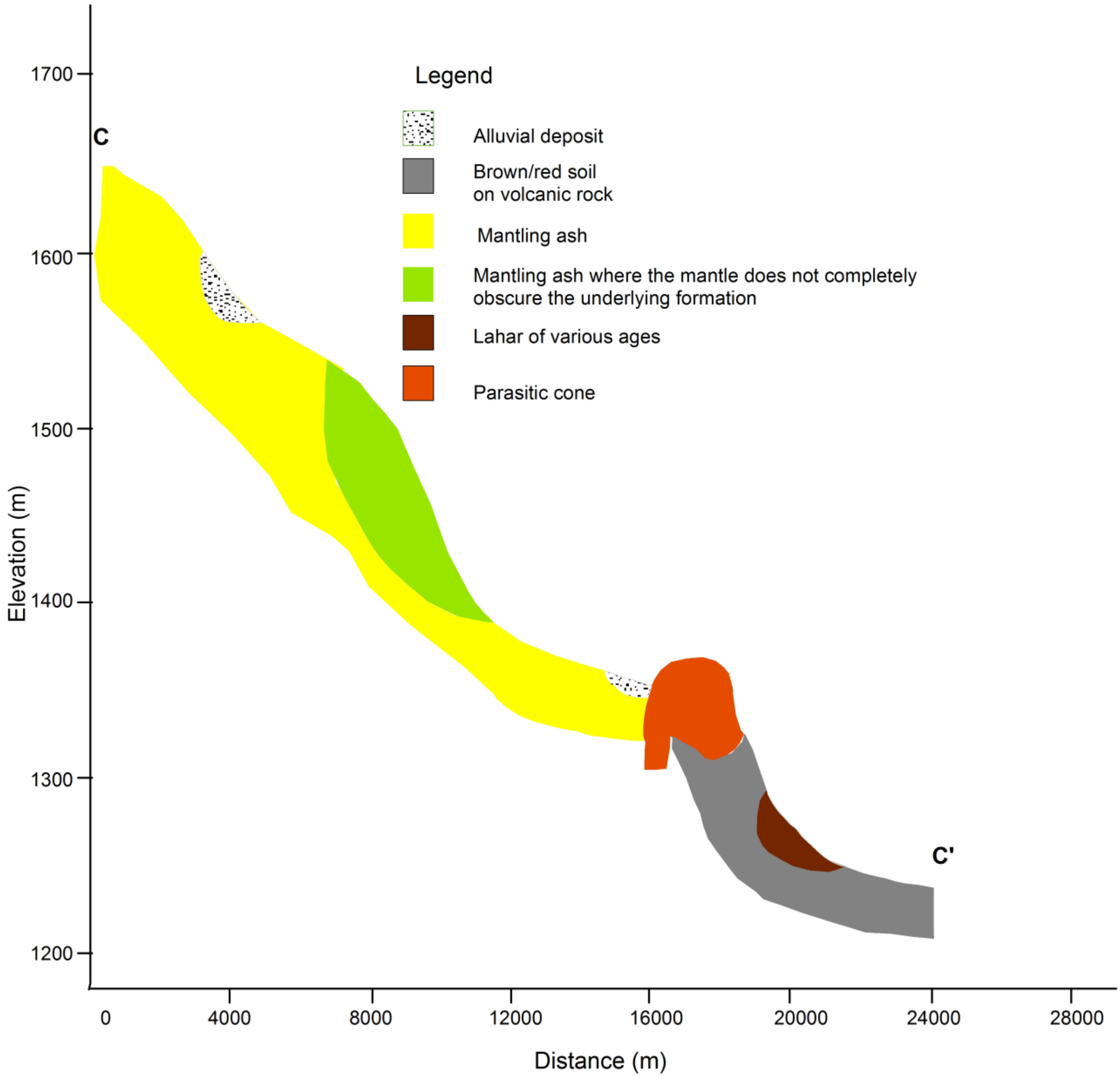

Figure 10: Geological cross section C-C´ from the steep slopes of Mt. Meru towards the foot of the Mountain.

3.3 Materials and methods

3.3.1 Field work and groundwater sampling

Mapping and geo-referencing using a hand-held global positioning system (GPS), GARMIN GPSmap62S was conducted to identify operational water wells and springs in the study area. A total of 46 drilled wells were identified out of which 30 deep wells (>50 m) and 3 shallow wells (<15 m)) were used in sampling campaign together with 12 natural springs (Fig. 9). Based on available well's construction records, most wells in the study area are tapping water at different depths depending on screen positions. This suggests that majority of collected water samples represented mixed groundwater from different layers. According to the hydrogeological setting of the study area and field work, two types of springs namely fracture and depression springs were observed (Bryan, 1919). Groundwater samples were collected during April and May, 2016 representing wet season in the study area.

In situ measurements of pH, temperature, electrical conductivity (EC), total dissolved solids (TDS) and salinity were carried out using Multi-parameter HANNA instrument, Model HI 9828. Equipment calibration was done prior to taking measurements according to the procedures set out by manufacturer.

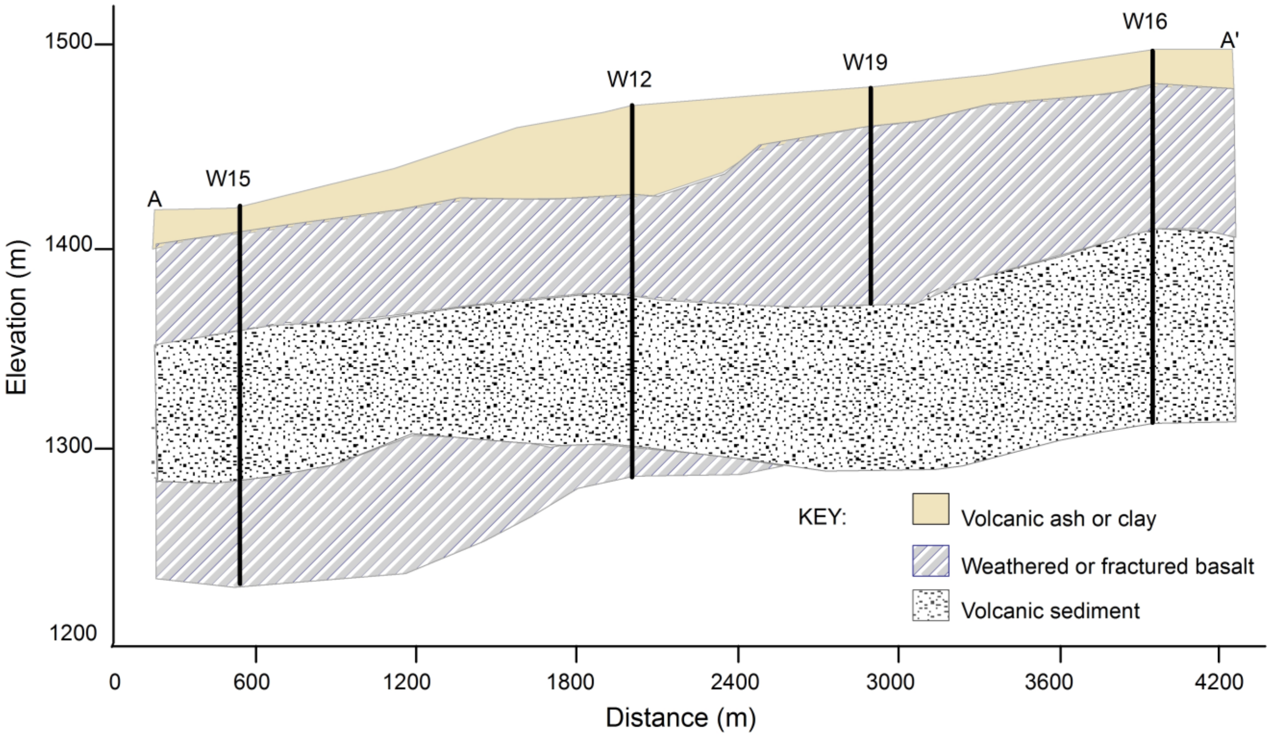

Figure 11: Geological section A-A´ derived from well lithology logs in the study area

Water samples were collected directly from taps located near the well heads into HDPE plastic bottles. Aliquots of samples earmarked for the analyses of Sodium (Na^+), potassium (K^+), magnesium (Mg^{2+}), calcium (Ca^{2+}), iron (Fe^{2+}) and manganese (Mn^{2+}) were acidified using ultrapure concentrated nitric acid, HNO_3 to a pH less than 2.0. All samples were stored in a refrigerator at 4°C to minimize microbial activity and any undesirable physical-chemical reaction before performing measurements of other chemical parameters including sulfate

(SO_4^{2-}), chloride (Cl^-), nitrate (NO_3^-), bicarbonate (HCO_3^-), fluoride (F^-) and phosphate (PO_4^{3-}) (Sundaram *et al.*, 2009; APHA, 2012).

3.3.2 Laboratory analyses

All groundwater samples were analyzed for major cations and anions using various methods. Bicarbonate (HCO_3^-) was determined by titration method using standard sulfuric acid and bromcresol green indicator for end point detection. The determination of SO_4^{2-} (SulfaVer 4 method), NO_3^- (Cadmium reduction method), and PO_4^{3-} (PhosVer 3, Ascobic acid method) were carried out using HACH DR 2800 spectrophotometer by powder pillow test. Chloride concentration was determined by Argentometric titration method using standard silver nitrate ($AgNO_3$) titrant and potassium chromate indicator solution (APHA, 2012). Fluoride content was determined by ion selective electrode method. The fluoride concentration was read directly from the meter calibrated with standard fluoride solution before use. Fluoride buffer was prepared from glacial acetic acid, sodium chloride and 1, 2-cyclohexylenediaminetetraacetic acid.

All major cations (Na^+, K^+, Mg^{2+}, Ca^{2+}) and trace elements (Fe^{2+} and Mn^{2+}) analyses were carried out at the Ardhi University Laboratory in Dar es Salaam by Atomic absorption Spectrometer (AAS) PerkinElmer Analyst 100. Samples were filtered (0.45 µm) before introduced into the flame for conversion from aerosols into atomic vapour which absorbs light from the primary source. The concentration of individual element was determined by measuring the amount of light absorbed relative to the standard solution under a specific wavelength. The accuracy of the major ions analyses was checked by calculating the charge balance error.

3.3.3 Geostatistical analysis

Cluster analysis, multivariate statistical analysis technique, was carried out using Paleontological Statistics (PAST) Software Package, Version 3.08 (Hammer *et al.,* 2001). The technique was employed to understand the relationship between variables from different sampling sites and their relevance with respect to groundwater quality in the study area. The clusters were established based on similarities of variables under consideration (Davidson & Ravi, 2005; Mooi & Sarstedt, 2010). One way ANOVA, single factor was used to compare means of various parameters between spring and well waters. It was also applied for comparing means of different water groups generated by cluster analysis. The correlation analysis was carried out for hydrogeochemical characteristics of analyzed water samples and the significance of correlation coefficients were tested using the statistical software, SPSS version 21. A geographical Information System (GIS) Software Package, ArcGIS version 10.1 was used to generate various maps in this study. Geostatistical analysis tool was employed in establishing groundwater quality spatial variation.

3.3.4 Piper diagram

Piper diagram was used to graphically represent chemistry of groundwater samples in the study area (Piper, 1944; Sadashivaiah *et al.*, 2008; Srinivas *et al.*, 2014). It comprises of three plots; a ternary diagram in the lower left representing the cations, another ternary diagram in the lower right representing the anions and a diamond plot in the middle representing a combination of the two ternary diagrams. The piper diagram was created using GW_Chart v.1.29.0 and it was employed to understand and identify different water composition or type through chemical relationships among groundwater samples (Utom *et al.*, 2013).

3.4 Results

3.4.1 Variation in physical-chemical properties

The results of groundwater physical chemical characteristics in the study area are presented in Table 4. The temperature for the spring water ranged from 16.7 to 22.9 °C and averaged 19.9 ±1.9 °C, while that of well water ranged from 19.4 to 24.5 °C and averaged 21.9 ±1.1 °C. The lowest temperature in spring water was recorded at high altitude about 1600 m above sea level (a.s.l.) and the highest temperature at an elevation of 1322 m a.s.l. A slight temperature variations observed in both spring and well waters are generally influenced by different ambient conditions from low to high elevations than aquifer type. The average value of pH in spring and well waters were 7.2 ± 0.7 and 7.5 ± 0.5 respectively. In spring water the pH varied from 6.42 to 8.26, while in well water it ranged from 6.47 to 8.9. About 42% and 15% of spring and well waters showed slightly acidic conditions (pH values less than 7.0), respectively.

Electrical conductivity (EC) in well water varied from 286 to 1634 µS/cm with an average value of 638 ± 330 µS/cm which is relatively high to WHO recommended limit (500 µS/cm). Low EC values were detected in spring waters which ranged from 157 to 781 µS/cm with an average value 399 ± 225 µS/cm.

Table 4: Groundwater chemistry in the study area

SN	Location	SID	pH	Temp	EC	TDS	Sal.	SO_4^{2-}	NO_3^-	F^-	Cl^-	HCO_3^-	PO_4^{3-}	Na^+	K^+	Mg^{2+}	Ca^{2+}	Fe^{2+}	Mn^{2+}
1	Lemara spring	S01	6.56	22.9	**781**	422	0.4	43	2.9	**1.78**	59.02	264	0.49	92.20	**21.93**	15.04	49.64	0.09	0.05
2	Ilboru Spring	S02	7.03	20.3	311	166	0.2	10	4.2	1.35	5.04	243	0.31	42.58	**15.46**	12.09	19.39	**1.93**	0.01
3	Kiranyi Spring	S03	7.92	20.4	467	251	0.2	13	6.0	**3.66**	12.23	195	0.55	84.34	**24.32**	12.66	15.36	0.11	<0.01
4	Engarendolu	S04	6.56	21.5	**671**	362	0.4	19	**17.3**	**1.88**	32.44	280	0.55	85.06	**37.35**	14.40	35.38	0.03	<0.01
5	LSB Spring	S05	6.42	19.6	398	214	0.2	20	**10.9**	1.18	5.32	290	0.30	76.73	**17.62**	13.69	37.51	0.07	0.01
6	Masama Chini	S06	8.26	16.8	165	88	0.1	0	1.6	**3.28**	2.66	170	0.34	41.33	6.58	3.70	6.13	**0.88**	<0.01
7	Masama Kati	S07	7.83	16.7	162	86	0.1	1	1.9	**3.01**	3.19	160	0.45	44.72	7.24	3.45	4.58	0.07	0.01
8	Masama Juu	S08	8.10	18.1	158	84	0.1	1	1.7	**2.71**	2.66	160	0.41	46.57	7.82	3.25	4.41	0.06	0.01
9	Machare Spring	S09	6.42	21.6	350	187	0.2	12	7.8	0.81	15.95	268	1.02	79.18	7.12	13.96	31.64	0.05	<0.01
10	Baraa Spring	S10	6.76	20.3	209	111	0.1	0	2.1	1.45	2.66	216	0.42	51.45	7.05	9.70	14.31	0.08	0.01
11	Selian Spring	S11	7.03	20.5	**744**	403	0.4	22	2.5	**5.45**	13.19	180	0.35	152.96	**14.73**	10.85	25.14	0.05	<0.01
12	Njoro Spring	S12	7.67	19.9	376	202	0.2	2	2.4	**5.36**	2.13	190	0.49	57.77	**20.72**	2.67	8.73	0.06	<0.01
13	Sombetini Sec	W01	7.18	22.6	**601**	323	0.3	11	8.8	**3.50**	26.31	188	1.02	84.62	**28.09**	9.51	17.51	0.10	0.07
14	Sokoni I	W02	8.90	24.3	**1114**	**606**	0.6	14	0.7	**3.87**	98.10	228	0.58	141.79	**26.02**	5.54	10.67	0.06	<0.01
15	Sokoni I P/S	W03	7.28	24.5	**833**	450	0.4	20	1.0	**4.53**	69.14	256	1.29	115.84	**25.41**	11.98	25.90	0.06	**0.33**
16	Emco	W04	7.73	21.6	450	241	0.2	5	0.5	**3.27**	18.64	264	0.19	76.98	**20.17**	11.66	18.00	0.08	0.02
17	Lemara P/S	W05	6.59	22.7	**640**	344	0.3	26	5.3	**1.75**	60.41	270	0.50	89.72	**27.72**	14.10	50.28	0.12	<0.01
18	Omahe	W06	7.49	21.0	**1216**	**667**	0.7	40	0.7	**2.61**	143.29	354	0.42	189.50	**56.03**	13.56	45.56	0.04	<0.01
19	Old Sanawari	W07	7.36	21.4	305	163	0.2	3	0.6	**2.28**	4.25	210	0.68	46.45	**12.22**	9.86	12.77	0.08	<0.01
20	Ilkiloriti	W08	7.50	21.3	362	193	0.2	6	2.0	**5.84**	5.32	238	1.48	103.17	8.87	5.24	4.86	**0.32**	0.01
21	Moivo II	W09	7.89	21.1	369	198	0.2	12	1.3	**1.99**	5.85	208	0.84	54.22	**12.47**	9.12	8.40	0.13	0.01
22	Sanawari primary	W10	7.94	21.4	380	203	0.2	4	0.8	**3.12**	7.44	223	0.85	54.52	**13.22**	7.75	9.68	**0.54**	<0.01
23	Lorovani Bondeni	W11	7.71	20.5	328	176	0.2	5	0.9	**4.88**	3.19	205	1.22	51.15	**13.51**	4.35	5.31	0.07	0.01
24	Oltulelei	W12	7.12	19.4	382	205	0.2	6	2.6	**4.22**	6.91	211	1.00	73.88	**16.54**	7.79	9.96	0.04	0.01
25	Ilkiurei	W13	7.84	22.0	494	265	0.3	7	4.2	**6.03**	22.76	215	0.98	88.88	**15.23**	4.70	8.14	0.06	<0.01
26	Loruvan Yard	W14	7.65	21.1	336	180	0.2	4	1.8	**3.73**	4.79	245	1.00	117.44	**15.71**	8.51	9.86	0.07	0.01
27	Kiranyi Mission	W15	7.37	21.7	468	251	0.2	11	1.3	**4.47**	15.04	254	0.83	93.87	**18.02**	8.46	12.68	0.07	<0.01

Table 4 (continued)

SN	**Location**	**SID**	**pH**	**Temp**	**EC**	**TDS**	**Sal.**	**SO_4^{2-}**	**NO_3^-**	**F^-**	**Cl^-**	**HCO_3^-**	**PO_4^{3-}**	**Na^+**	**K^+**	**Mg^{2+}**	**Ca^{2+}**	**Fe^{2+}**	**Mn^{2+}**
28	Lorovani No. 4	W16	7.60	20.6	304	162	0.2	2	2.0	**2.09**	8.51	260	1.14	75.20	**13.12**	9.93	12.30	0.06	0.02
29	Mianzini	W17	8.27	21.7	433	232	0.2	7	0.9	**6.73**	9.57	230	1.36	78.63	11.38	2.62	2.43	0.11	0.02
30	Sakina	W18	7.56	21.5	456	244	0.2	7	1.4	**5.72**	6.91	210	1.13	64.25	**16.07**	6.00	9.63	0.19	0.01
31	Iliboru Sec	W19	7.95	21.2	385	206	0.2	6	0.4	**9.23**	5.85	225	1.44	105.21	**12.98**	2.35	2.40	**0.36**	0.01
32	Burka P/S	W20	7.18	22.3	**738**	399	0.4	20	**10.1**	**3.11**	36.91	370	0.48	95.18	**34.81**	14.24	60.20	0.02	0.04
33	Moilo	W21	7.98	21.3	**560**	301	0.3	18	0.7	**6.17**	9.66	280	0.59	99.96	**30.67**	5.29	18.81	0.03	0.07
34	Moilo II	W22	8.09	23.1	**1634**	**902**	0.9	40	1.0	**10.80**	174.25	292	0.84	231.38	**71.68**	8.90	16.71	0.03	0.01
35	Missiori	W23	7.54	20.2	**956**	**522**	0.5	43	2.9	**6.32**	86.38	250	0.48	137.81	**51.94**	7.75	28.79	0.03	<0.01
36	Mnadani No.2	W24	7.49	22.1	**796**	430	0.4	21	2.8	**6.21**	74.25	286	0.82	139.61	**36.90**	10.17	23.47	0.26	<0.01
37	Mnadani No.3	W25	8.43	22.3	**962**	**523**	0.5	37	1.5	**6.65**	87.85	270	0.71	167.50	**52.88**	9.44	33.03	0.03	0.01
38	Magereza	W26	7.40	22.8	**1073**	**585**	0.6	29	0.2	**3.26**	114.84	350	0.64	146.45	**62.68**	13.74	39.18	0.04	0.06
39	Engutoto	W27	7.15	22.9	**1024**	**557**	0.6	69	0.1	**1.83**	144.10	360	0.34	144.12	**31.96**	15.59	56.20	**3.06**	**0.34**
40	Thomas Boma CR	W28	6.48	22.2	286	152	0.1	11	1.7	0.60	3.19	290	0.68	73.95	3.15	13.62	26.55	0.23	<0.01
41	Baraa P. Post	W29	6.47	21.3	369	197	0.2	9	4.5	0.68	5.32	310	0.41	75.26	8.45	14.11	41.88	0.05	0.02
42	Banana No.4	W30	7.32	22.5	443	237	0.2	0	1.8	**1.74**	4.13	280	1.01	55.50	**14.84**	13.20	23.75	**2.90**	**0.22**
43	OLSS	W31	6.96	21.7	**802**	435	0.4	12	6.8	1.13	55.95	390	0.45	100.52	**25.07**	14.75	74.83	0.08	0.01
44	Lukindo	W32	7.06	24.0	**997**	**541**	0.5	63	6.7	**3.51**	103.83	243	0.45	126.52	5.23	14.74	57.16	0.05	0.09
45	Banana No.5	W33	6.85	22.1	**571**	307	0.3	27	2.5	1.38	48.51	346	0.34	113.23	**21.06**	12.76	40.51	0.04	0.01
	WHO Guideline		6.5-8.5	30-35	500	500		250	10	1.5	250	500	6	200	12	50	75	0.3	0.1

All units are in mg/L except pH (unitless), EC (µS/cm), Temperature (°C), Salinity (‰) and n=45

3.4.2 Major cations and anions

About 89% of the groundwater samples analyzed (Table 4) in the study area gave charge balance errors less than ±10% which is acceptable in most fresh groundwater hydrogeochemical assessment (Srinivasamoorthy *et al.*, 2008; Utom *et al.*, 2013; Srinivas *et al.*, 2014). The rest of the samples showed relatively high charge balance error greater than 10% which is probably due to low ionic strength (mean value = 0.0082) of water samples (Fritz, 1994). The overall mean charge balance error was estimated to -6.25% which is fairly reasonable for accuracy check. Figure 12 shows major ions composition of both spring and well waters in the study area. The groundwater chemistry is typically Sodium-Potassium Bicarbonate. The concentration of sodium (Na^+) was relatively higher than other cations in all samples from spring and well waters (Table 4).

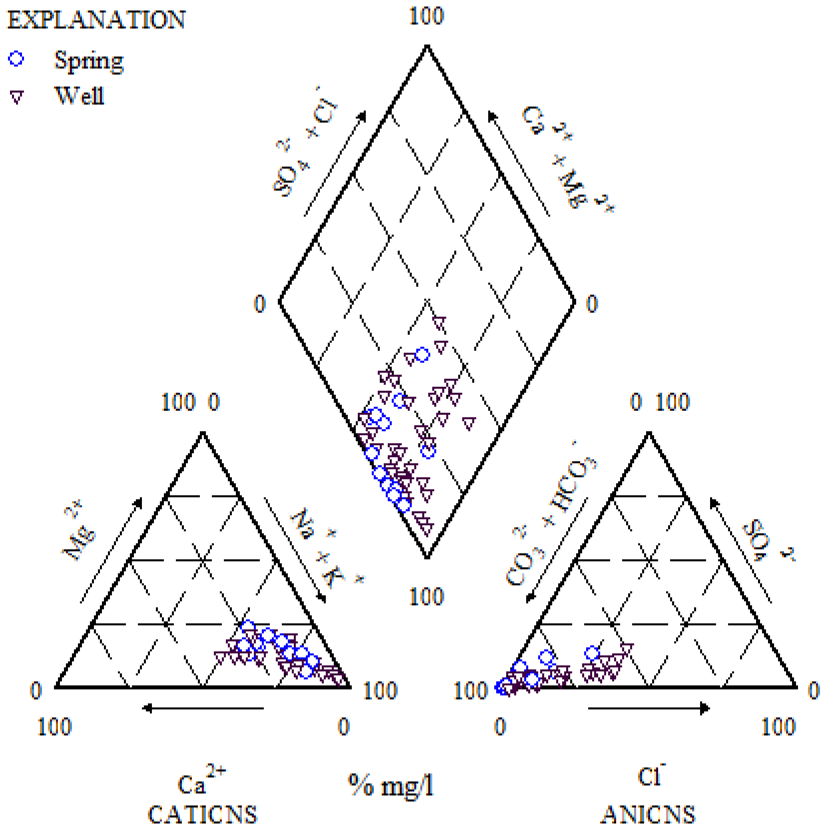

Figure 12: Piper diagram for chemical composition of groundwater in the study area

Fluoride in the study area was generally high in both spring and well waters. In well water, its concentration varied from 0.60 mg/l to 10.8 mg/l with average value of 4.04 ± 2.39 mg/l. Samples from springs were observed to have relatively low concentration ranging from 0.81 to 5.45 mg/l with mean value 2.66 ± 1.56 mg/l. About eighty two (82) percent of the analyzed groundwater samples indicated fluoride concentrations higher than WHO guidelines and Tanzanian drinking water standards (1.5 mg/l) (Table 4). The concentrations of fluoride in groundwater indicated a consistent relationship with amount of pH, HCO_3^-, $Ca^{2+,}$ and EC. Samples with high pH (alkaline condition), EC and HCO_3^- mostly in well waters were found to have high fluoride concentrations. There was a significant positive relationship between fluoride and pH, r (31) = 0.62, $p < 0.01$), however the correlation between fluoride and EC (r=0.29) was not statistically significant. Moreover, fluoride showed significant negative correlation with alkaline earth elements, Ca^{2+} (r (31) = -0.47, p = 0.006) and Mg^{2+}(r (31) = -0.69, $p < 0.01$) and significant positive relationship with Na^+, r (31) = 0.426, p = 0.013 (Table 5).

In well water, nitrate concentration levels varied from 0.1 to 10.1 mg/l with average value of 2.4 ± 2.51 mg/l. Spring waters were found with relatively high nitrate levels, ranged from 1.6 to 17.3 mg/l and averaged 5.11 ± 4.80 mg/l. Only three out of forty five analyzed groundwater samples (S04, S05 and W20) exceeded the recommended WHO drinking water limit of 10 mg/l beyond which it may cause health effects such as infant methemoglobinemia (Fan & Steinberg, 1996; Adelana, 2005).

The levels of both sulphate and chloride were relatively low compared to recommended WHO drinking water limit (250 mg/l). The maximum levels of sulphate detected were 43 mg/l and 69 mg/l in spring and well waters, respectively. The maximum chloride level in well water was 174 mg/l and 59 mg/l in spring water. The two constituents (SO_4^{2-} and Cl^-) seemed to be related in both spring and well water samples. Figure 13 shows significant strong positive correlation between sulphate and chloride with Pearson coefficients, r (10) = 0.879, $p < 0.01$ and r (31) = 0.858, p < 0 0.01 for spring and well waters, respectively.

Relatively low concentrations of dissolved phosphate were observed in most spring water and shallow wells with exception of sample S09 which recorded 1.02 mg/L (Table 4). High levels of phosphate (up to 1.48 mg/l) were observed in deep wells (>100 meters deep). The possible source of phosphate release into groundwater is apatite minerals which are common in volcanic rocks of Mt. Meru region (Roberts, 2002). Figure 14 shows significant positive correlation between phosphate and well depth, r (23) = 0.547, p = 0.005. The correlation indicates that phosphate minerals are more pronounced in deep geological formation of the study area.

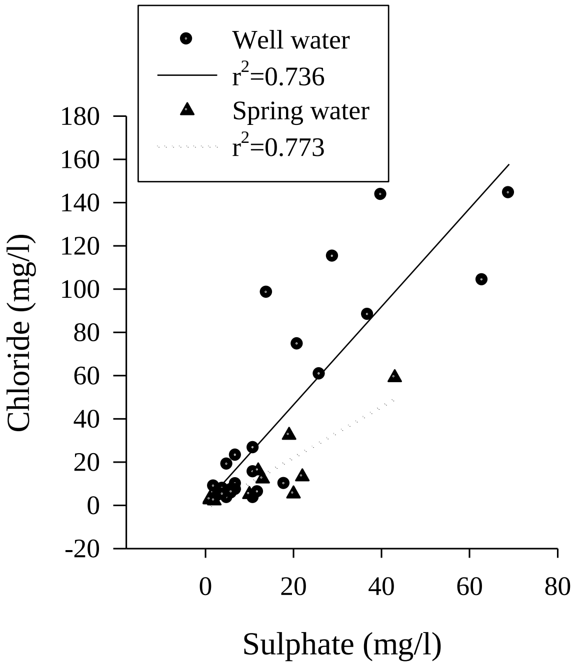

Figure 13: Scatter plot Sulphate and Chloride

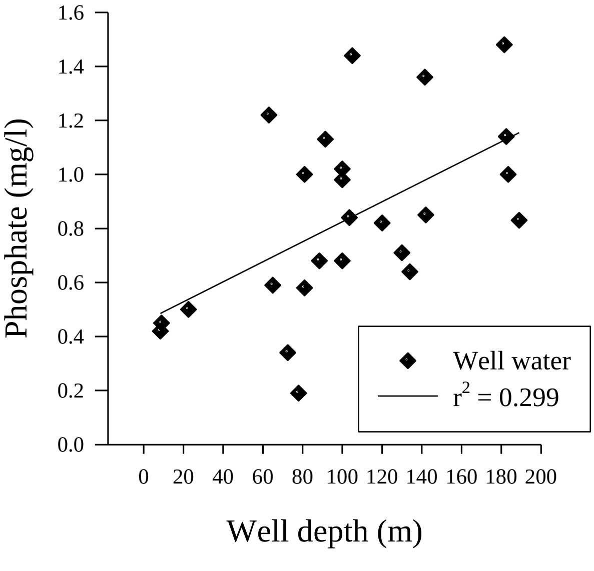

Figure 14: Phosphate variations with well depth

3.4.3 Trace elements (Fe and Mn)

Iron concentration varied from 0.02 to 3.06 mg/l (well water) and 0.03 to 1.93 mg/l (spring water). More than 84% of the analyzed water samples had Fe contents less than recommended maximum WHO limit (0.3 mg/l). Furthermore the concentration of Manganese was generally very low. About 36% of analyzed water samples were below the detection limits (0.01 mg/l). However, only two samples (W03 and W27) out of forty five were observed to have manganese levels beyond the recommended WHO guideline (0.1 mg/l). Generally, the levels of iron and manganese detected in this study were relatively low which have no significant health effect or engineering problems in water supply infrastructures.

3.4.4 Multivariate analysis

Analyzed water samples were grouped into four main categories, the first group comprises of cluster A and B with a total of fourteen samples which indicated great than 60% similarity. Six out of fourteen in this group being samples from spring water. Cluster C has a total of six (6) sampling sites all being wells. The third group (Cluster D) has twelve (12) sampling sites with great than 60% similarity and one of its sub-clusters has greater than 90% similarity index. The last group (Cluster E) comprises of four (4) sampling sites (springs) with great than 95% similarity. However, out of 45 sampling sites, five showed less than 50% similarity with other clusters (Fig. 15).

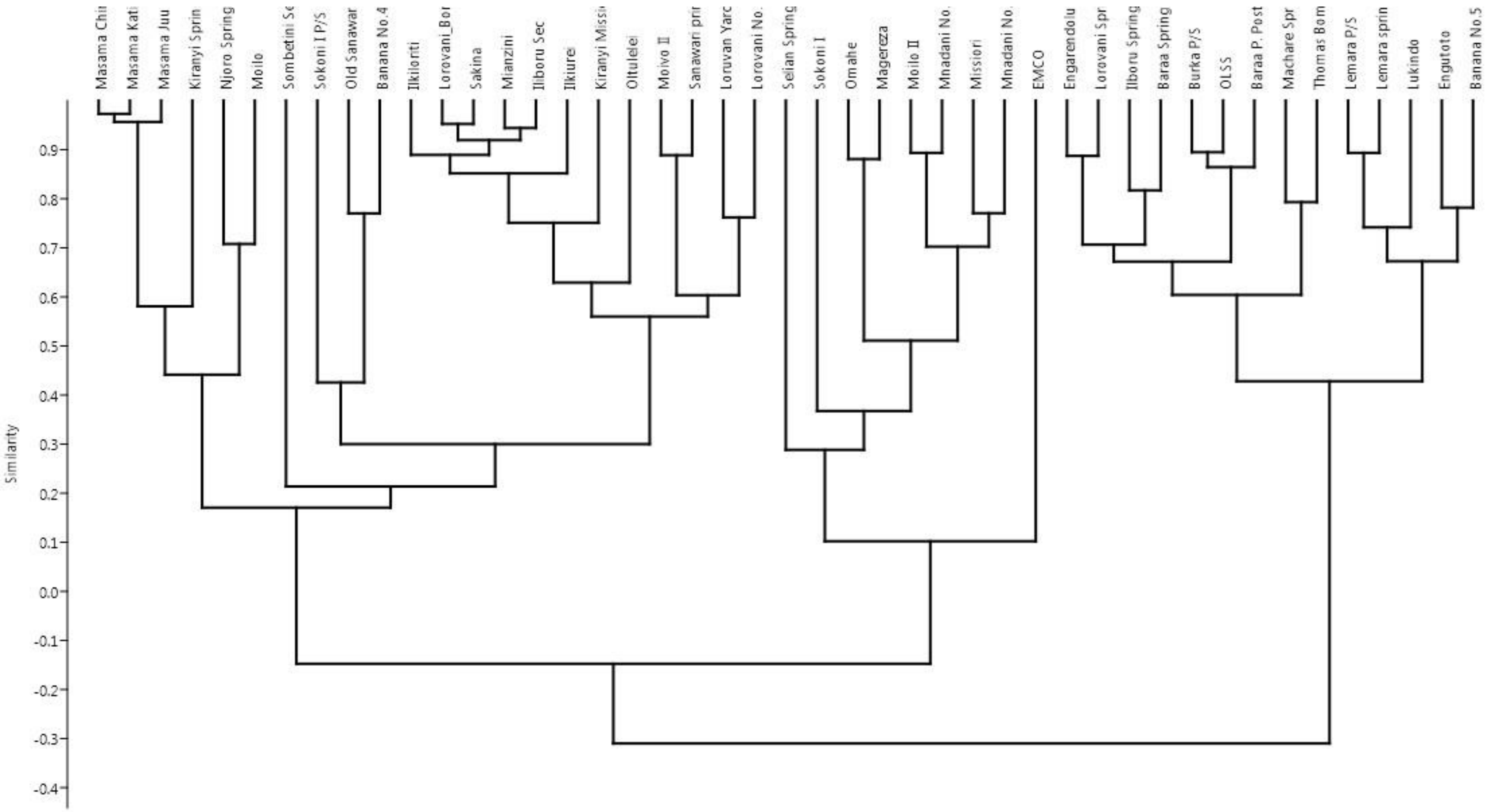

Figure 15: Dendrogram for groundwater hydrogeochemical data from 45 sampling sites

3.5 Discussion

3.5.1 Groundwater chemistry

The results of major ions for groundwater plotted in piper diagram (Fig. 12) indicated both spring and well waters to fall under Sodium-Potassium Bicarbonate water type. The chemical properties of groundwater are dominated by alkali elements (Na^+ and K^+) and weak acids (HCO_3^-). Sodium ion was generally dominant in all samples with Magnesium being the least cation in the study area ($Na^+ > Ca^{2+} > K^+ > Mg^{2+}$). Such chemical behavior in groundwater is explained by cations exchange reactions between Na^+ and Ca^{2+} which occur as a result of water-rock interaction as water moves through different mineralogical composition (Cerling *et al.*, 1989; Ghiglieri *et al.*, 2012; Utom *et al.*, 2013) as well as dissolution of trona which is dominant in the East African Rift system (Kaseva, 2006; Pittalis, 2010). The ions distribution (Fig. 12) and significant positive correlation (Table 5) between bicarbonate ion and major cations, Ca^{2+}($r (31) = 0.81$, $p < 0.01$), Mg^{2+}($r (31) = 0.70$, $p <0.01$), Na^+($r (31) = 0.44$, $p = 0.011$) and K^+($r (31) = 0.44$, $p = 0.010$) in well water indicate that these constituents are naturally occurring through weathering and water-rock interaction mechanisms (Srinivasamoorthy *et al.*, 2012; Ishaku *et al.*, 2015). The same trend of positive correlation was also observed in spring water (Table 6). From other literature it's also suggested that in geothermal system, most of HCO_3^- and part of alkali elements are produced by the reactions of dissolved carbon dioxide (CO_2) with rocks (Gizaw, 1996). Generally, both well and spring waters in the study area were characterized by same water type (Na-K-HCO_3) as presented in the piper diagram. However, spring water contains significantly less dissolved ions (Table 7) compared to well water (Fig. 16). Based on field observation most springs are originating from aquifers which are highly influenced by rainfall. Their discharges increase significantly during or immediately after rainy season i.e., water-rock interaction time is relatively short hence less dissolved ions. The hydrochemistry of groundwater in the study area particularly deep wells is mainly controlled by geochemical reactions and natural processes than anthropogenic influences. The water type (Na-K-HCO_3) and distribution of major cations and anions in the piper diagram indicate that groundwater hydrochemistry is mainly influenced by aquifer lithology and dissolution of trona which is mainly affecting shallow aquifers.

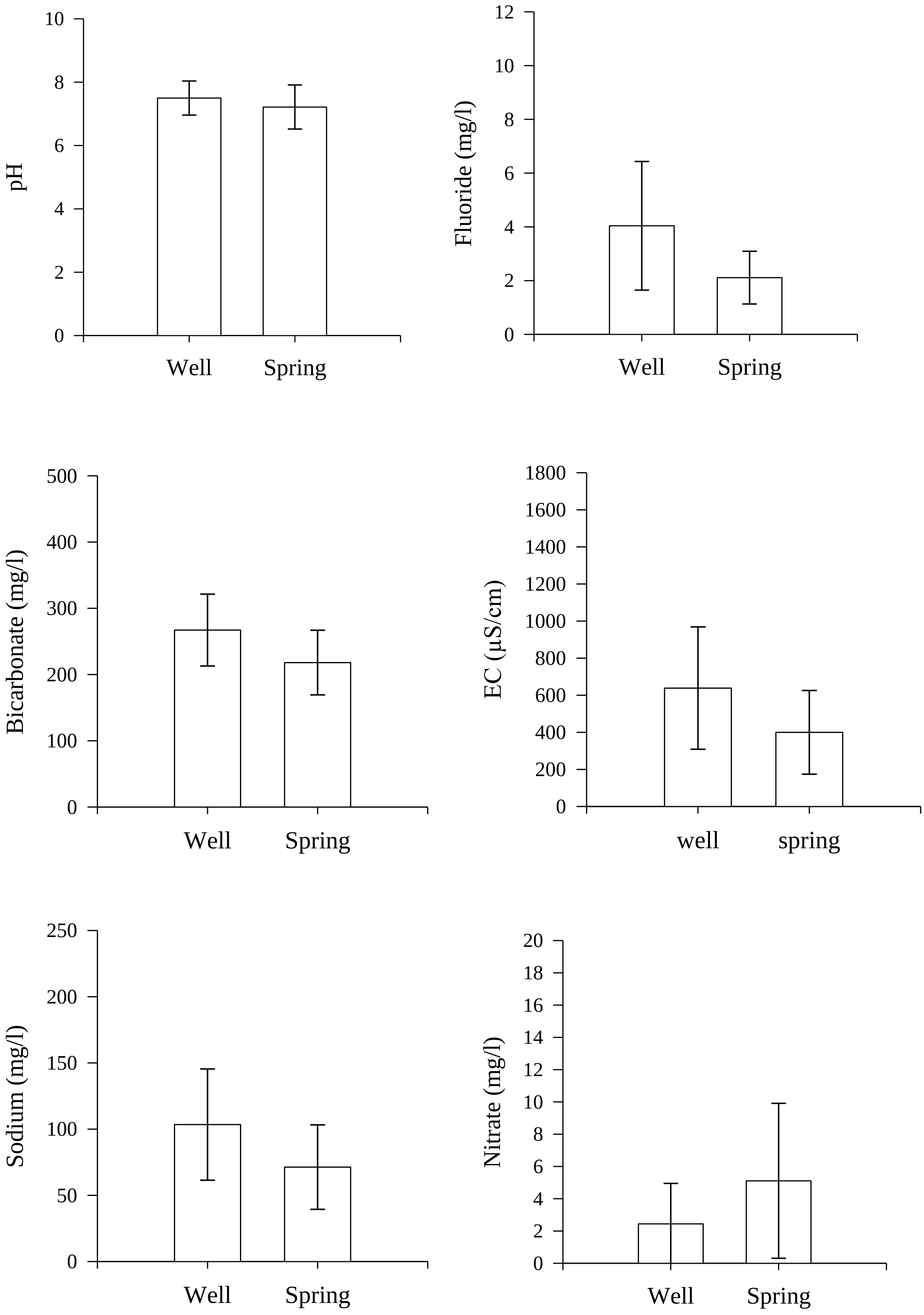

Figure 16: Comparison of means of selected major ions in spring and well waters

Table 5: Pearson correlation matrix for samples from well water

	pH	Temp	EC	TDS	Sal.	SO_4^{2-}	NO_3^-	F^-	Cl^-	HCO_3^-	PO_4^{3-}	Na^+	K^+	Mg^{2+}	Ca^{2+}
pH	1														
Temp	0.04	1													
EC	0.21	0.53	1												
TDS	0.21	0.53	1.00	1											
Sal.	0.24	0.47	0.99	0.99	1										
SO_4^{2-}	-0.10	0.40	0.76	0.76	0.75	1									
NO_3^-	-0.45	0.14	0.03	0.03	-0.01	0.08	1								
F^-	0.62	-0.02	0.29	0.30	0.29	0.07	-0.24	1							
Cl^-	0.11	0.51	0.97	0.97	0.97	0.84	-0.04	0.18	1						
HCO_3^-	-0.38	0.19	0.45	0.45	0.45	0.44	0.17	-0.34	0.49	1					
PO_4^{3-}	0.30	-0.17	-0.39	-0.39	-0.38	-0.51	-0.21	0.48	-0.43	-0.60	1				
Na^+	0.24	0.37	0.90	0.90	0.90	0.70	-0.10	0.43	0.89	0.44	-0.26	1			
K^+	0.23	0.18	0.83	0.83	0.84	0.54	-0.07	0.36	0.78	0.44	-0.31	0.81	1		
Mg^{2+}	-0.69	0.35	0.30	0.30	0.28	0.45	0.36	-0.69	0.39	0.70	-0.67	0.17	0.19	1	
Ca^{2+}	-0.55	0.33	0.46	0.45	0.43	0.61	0.52	-0.47	0.50	0.81	-0.70	0.31	0.30	0.84	1

Green color indicates negative correlation ($r < -0.5$) and pink color, positive correlation ($r > 0.5$)

As to a large extent the hydrogeological formation of the region is characterized by the presence of sodium and potassium rich minerals such as nepheline, chabazite, sanidine, cancrinite, phillipsite and anorthoclase to mention few (Ghiglieri *et al.*, 2012). Generally, sodium and potassium ions were relatively high in all groundwater samples (Table 4) indicating the influence of water-rock interaction in determining groundwater chemistry of the study area. This is also supported by low levels of anthropogenic indicators such as nitrate, chloride and sulphate observed in deep wells (Table 4).

Moreover, statistical error bars of selected major ions were plotted to compare water clusters (Fig. 17). A slight difference between clusters was observed from the error bar plots. Additionally, the results of statistical test using one way ANOVA, single factor indicated a significance difference between clusters for the selected major ions (Table 8). The differences shown between clusters are probably due to heterogeneity of the volcanic aquifers in the study area (Ong'or & Long-cang, 2007). However, the groundwater hydrochemistry of the study area remain the same with Na-K-HCO_3 water type.

Table 6: Pearson correlation matrix for samples from spring water

	pH	Temp	EC	TDS	Sal.	SO_4^{2-}	NO_3^-	F^-	Cl^-	HCO_3^-	PO_4^{3-}	Na^+	K^+	Mg^{2+}	Ca^{2+}
pH	1														
Temp	-0.76	1													
EC	-0.53	0.76	1												
TDS	-0.53	0.76	1.00	1											
Sal.	-0.55	0.74	0.98	0.98	1										
SO_4^{2-}	-0.61	0.74	0.88	0.88	0.84	1									
NO_3^-	-0.56	0.41	0.39	0.39	0.44	0.32	1								
F^-	0.57	-0.27	0.16	0.16	0.12	-0.17	-0.41	1							
Cl^-	-0.50	0.72	0.78	0.78	0.77	0.88	0.30	-0.23	1						
HCO_3^-	-0.88	0.71	0.46	0.45	0.48	0.60	0.74	-0.69	0.52	1					
PO_4^{3-}	-0.29	0.41	0.08	0.08	0.08	0.07	0.27	-0.26	0.25	0.29	1				
Na^+	-0.41	0.54	0.84	0.84	0.80	0.66	0.22	0.34	0.44	0.19	0.11	1			
K^+	-0.31	0.56	0.71	0.71	0.71	0.53	0.70	0.07	0.54	0.48	0.00	0.37	1		
Mg^{2+}	-0.81	0.82	0.66	0.66	0.64	0.75	0.61	-0.52	0.61	0.84	0.29	0.52	0.50	1	
Ca^{2+}	-0.85	0.81	0.77	0.77	0.76	0.91	0.56	-0.44	0.80	0.86	0.24	0.55	0.51	0.87	1

Green color indicates negative correlation ($r < -0.5$) and pink color, positive correlation ($r > 0.5$)

Table 7: One way ANOVA, Single factor results comparing spring and well waters

Ion/Parameter	Df	F	P-value	Sig. level, α
pH	1[a], 43[b]	2.06	**0.159**	0.05
EC	1[a], 43[b]	5.34	0.026	0.05
HCO_3^-	1[a],43[b]	7.58	0.009	0.01
F^-	1[a], 41[b]	6.09	0.018	0.05
Na^+	1[a], 43[b]	5.78	0.021	0.05
NO_3^-	1[a], 43[b]	5.93	0.019	0.05

[a] Degree of freedom between groups, [b] degree of freedom within groups

Table 8: One way ANOVA, Single factor results comparing water clusters

Ion/Parameter	Df	F	P-value	Sig. level, α
EC	4[a], 31[b]	22.98469	6.7E-09	0.01
Na^+	4[a], 31[b]	21.06345	1.8E-08	0.01
Ca^{2+}	4[a], 31[b]	19.99604	3.2E-08	0.01
F^-	4[a], 31[b]	9.916838	2.8E-05	0.01
Cl^-	4[a], 31[b]	29.21781	4E-10	0.01
NO_3^-	4[a], 31[b]	4.717767	0.004	0.01

[a] Degree of freedom between groups, [b] degree of freedom within groups

3.5.2 Fluoride

Fluoride concentration in the study area was generally high in both spring and well waters. Its concentrations varied from one location to another indicating different mineralogy or geological formation which may have different dissolution rate, cation exchange capacity and precipitation in the aquifer matrix (Ghiglieri *et al.*, 2012). Fluoride concentration indicated positive correlation with Na^+ and negative correlation with alkaline earth elements (Ca^{2+} and Mg^{2+}) (Table 5). This association indicates that during ionic exchange process and precipitation when calcium ion is removed from groundwater system more Na^+ and F^- ions are being released from minerals such as fluorapatite and nepheline in the aquifer matrix. Similar findings on fluoride behavior with alkaline earth elements (Ca^{2+}, Mg^{2+}) and alkali metals (Na^+, K^+) are well documented (Chae *et al.*, 2007; Rafique *et al.*, 2009; Guo *et al.*, 2012). Moreover, Ghiglieri *et al*. (2012) and Srinivasamoorthy *et al*., (2012) revealed that alkaline nature of groundwater enhances fluoride releases from fluorine rich-minerals such as fluorite (CaF_2) into water system. Furthermore, according to the batch experiments conducted (Saxena & Ahmed, 2001) at normal room temperature fluoride is easily released from parent rocks at a pH, EC and HCO_3^- range of 7.6 to 8.6, 750-1750 µS/cm and 350-450 mg/l respectively. These findings are in line with high fluoride concentrations detected in groundwater samples with high bicarbonate and pH values. In addition, water-rock interaction influences the concentration and rate of fluoride release into groundwater system. Low fluoride concentration in fractured and highly permeable phonolite hosted aquifers has been reported, and high fluoride concentration in water originating from basalt and lahars formation (Ghiglieri *et al.*, 2010). This suggests that variations of fluoride concentrations in groundwater are mainly controlled by both aquifer materials and mean residence time. The geological-hydrogeological section A-A´ (Fig. 11) constructed from well logs (Appendix 3) indicates that most wells collect water from volcanic sediment aquifers except W19 which is located in weathered and/or fractured basalt formation. W19 indicated high fluoride concentration (9.23 mg/l) compared to wells W12 (4.2 mg/l) and W16 (2.09 mg/l) which tap water from volcanic sediment aquifer.

However, it should be noted that groundwater samples were collected from different depths within a single well depending on the position of the screens (Table 9). In the study area the spatial distribution of fluoride concentrations indicates high fluoride concentration in northern and northwestern parts of the study area (Appendix 1). High fluoride concentration in this zone is probably due to dominance in basalt formation and other fluoride rich volcanic materials such as lahars and volcanic ash (Figs.10 and 11) which are known to contain and release significant amount of fluoride into groundwater in the region (Ghiglieri *et al.*, 2012). It is unfortunate that the northwestern part is one of the areas earmarked by water authority to have potential groundwater reserve for present and future use. It should be noted that groundwater reserve in this part is obviously reduced as its quality won't satisfy the intended use (Ako *et al.*, 2011; Currell *et al.*, 2012). However, the southern part of the study area shows relatively low levels of fluoride concentration compared to north and therefore calls for further groundwater exploration for future development.

Table 9: Well construction details indicating position of the screens

Well ID	Depth (m)	Screen position (m below ground surface)	Aquifer thickness covered by screens (m)
W10	142	44-52, 64-76, 80-124, 132-136	92
W12	184	80-100, 120-156, 162-176	96
W16	183	80-88, 100-108, 112-128, 136-168	88
W19	108	28-48, 64-70, 76-84, 88-96	68
W17	142	56-64, 72-120, 124-136	80

Source: The data were compiled from well lithology logs and construction details (Appendix 3)

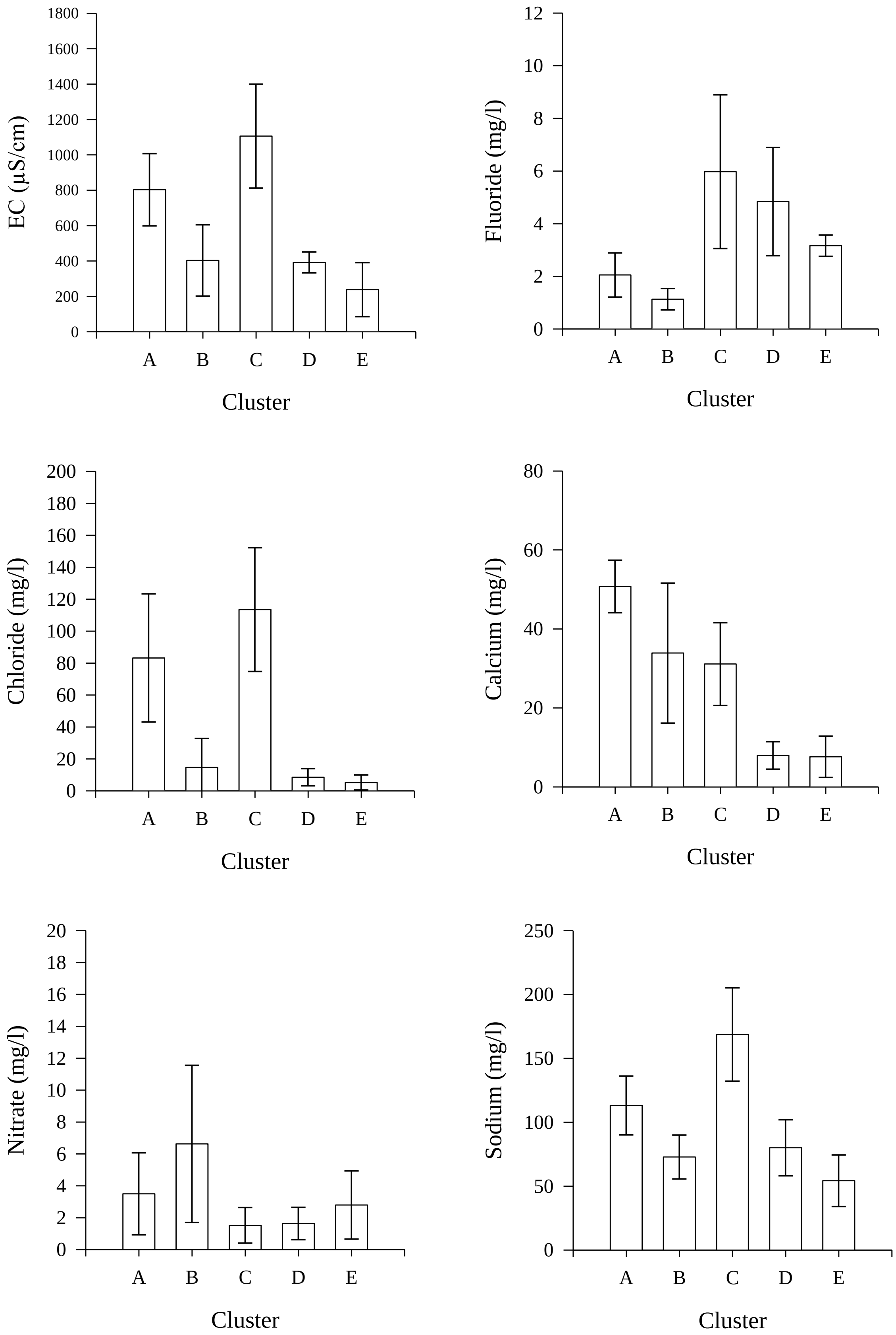

Figure 17: Comparison of means of selected major ions for different water clusters

3.5.3 Spatial distributions of nitrate, sulphate and chloride

Nitrate and other nutrients are amongst the best indicators of anthropogenic influence in groundwater quality assessment (Kaown *et al.*, 2009). Apart from on-site sanitation practice in the research area, urban agriculture and animal husbandry are also common. All these are likely to threaten the quality of groundwater for various uses including drinking and other domestic purposes. The chances of pollutants to be released and transported from these anthropogenic sources to the shallow aquifers are very high (Drechsel & Dongus, 2010).

Very low concentrations of nitrate, chloride and sulphate were observed in groundwater samples collected from northern part of the study area (Appendix 1). This suggests the influence of natural sources such as nitrogen leached from natural soils, volcanic minerals (e.g., apatite) and gases rather than anthropogenic activities. However, high concentrations of NO_3^-, Cl^- and SO_4^{2-} were observed in wells and springs (Appendix 1) located in highly populated urban areas (South of the study area) where the use of pit latrine and soak away pit as sanitary facilities is common. Additionally, effluent from a combined domestic and industrial wastewater treatment plant (waste stabilization ponds) is being used for irrigation purpose in southern part of the study area which is likely to cause groundwater contamination. Similar cases of groundwater contamination have been reported in Tanzania and other parts of the world (Nkotagu, 1996b; Mato & Kaseva, 1999; Kaown *et al.*, 2009; Elisante & Muzuka, 2015). In most cases, these wastes are discharged haphazardly to the environment (Couth & Trois, 2011; Laramee & Davis, 2013) or due to underground leakage from pit latrine, septic tanks and soak-away pit which are common sanitary facilities in the study area and Tanzania at large (Chaggu *et al.*, 2002; Jenkins *et al.*, 2014). Moreover, water samples collected from northwest and western part of the study area commonly known as Ngaramtoni and Magereza showed relatively high concentrations of both $Cl^{—}$ and $SO_4^{2—}$ (Appendix 1). The area is dominated by cultivation of coffee, wheat, sunflower, maize, and beans. Therefore, fertilizer application and uncontrolled waste disposal mainly domestic sewage may have also contributed to these constituents in groundwater. Generally, the quality of groundwater with respect to NO_3^-, Cl^- and SO_4^{2-} in the study area was generally good as the concentrations are still fairly below the recommended WHO guidelines with exception of samples S04, S05 and W20 which recorded high nitrate levels 17.3, 10.9 and 10.1 mg/l respectively possibly caused by human activities.

3.6 Conclusions

The hydrogeochemical assessment results and distribution of groundwater major cations (Na^+, Ca^{2+}, K^+, Mg^{2+}) and anions (HCO_3^-, Cl^-, SO_4^{2-}, F^-) in the study area indicate that groundwater chemistry is mainly influenced by aquifer lithology than anthropogenic activities. Groundwater in the study area is dominated by sodium and bicarbonate ions which define the general composition of the water type to be Na-K-HCO_3. With exception of fluoride and faecal contamination (not covered in this study) the quality of groundwater is generally suitable for drinking purpose and other socio-economic uses. Based on the hydrogeological investigation, two potential aquifers (volcanic sediment and weathered/fractured formation) have been identified both having substantial yield. Generally, the aquifers yield water containing significant concentration of fluoride exceeding WHO guidelines. Eighty two (82) percent of the analyzed groundwater samples indicated fluoride concentrations higher than WHO guidelines and Tanzanian drinking water standards (1.5 mg/l). The northern and northwestern parts of the study area indicated high fluoride concentrations in both well and spring waters than southern zone. As mentioned earlier, high fluoride concentration in northern and northwestern parts is probably due to dominance in basaltic formation and other fluoride rich volcanic materials such as lahars and volcanic ash which are known to contain and release significant amount of fluoride into groundwater in the region. However, a detailed geological studies need to be conducted to precisely inform the entire spectrum of fluoride distribution in the study area. Groundwater abstracted from the southern part of the study area is of better quality for human consumption than northern zones which is at high elevation on the foot of Mt. Meru. The influence of anthropogenic pollutants was observed in shallow wells and spring sources. This was evidenced by relatively high concentrations of nitrate, chloride and sulphate in samples collected from sources close to populated urban areas, wastewater effluent disposal zones, and croplands. Spring water sources should be protected from anthropogenic activities as they produce water of good quality in terms of key chemical parameters including fluoride which seems to be critical in the study area.

CHAPTER FOUR

GROUNDWATER ABSTRACTION AND AQUIFER SUSTAINABILITY IN ARUSHA WELLFIELD

Abstract

Groundwater discharges and drawdown measurements (2000-2016) from production wells in combination with climate data were considered to establish groundwater abstraction trends and possible impacts in Arusha wellfield. The findings revealed significant groundwater reserve depletion in the wellfield. Water level decline of about 1.0 m per year and reduction in well discharges of about 20 to 61% were observed from existing production wells for a period not exceeding 17 years. The results suggest that the Arusha wellfield is experiencing groundwater storage depletion which is partly due to over-abstraction and reduced groundwater recharge. Based on the available borehole data groundwater abstraction from Arusha wellfield was estimated to be 13 254 719 m^3/year which is far less than the current water demand (34×10^6 m^3/year). However, this amount is less than the actual amount of groundwater abstracted as most individual wells are drilled without getting water use permit.

The groundwater recharge was estimated to 13 035 880 m^3/year which is higher than estimated abstracted amount but less than the current city water demand. This indicates that the wellfield is already stressed due to groundwater over-abstraction. There is also evidence of decreasing rainfall amount and increasing temperature as a result of climate change which may contribute to groundwater depletion in the region. The quality of groundwater notably level of fluoride has significantly increased in some production wells to the extent of abandoning them from public water supply system.

Keywords: Groundwater abstraction, wellfield, groundwater recharge

4.1 Introduction

Groundwater has been used globally as a reliable source of water supply as surface water is facing a number of challenges and therefore, not a reliable and dependable source in terms of quality and quantity at any one time (Mato, 2002; Lu *et al.*, 2015). Groundwater is not easily affected by impact of climate variability such as prolonged drought which is seriously affecting surface water resources such as rivers and streams (Taylor *et al.*, 2013; Chang *et al.*, 2015). Furthermore, groundwater is not as vulnerable to pollution as surface water sources. Hence, it requires less treatment effort prior human consumption. Because of advantage of groundwater resource being less vulnerable to pollution and can be available in most places worldwide its exploitation has been tremendously increasing globally in both humid and semi-arid regions. Intensive groundwater abstraction has been reported in different parts of the world including Europe, China, United States of America, Iran, India, and Pakistan (Wada *et al.*, 2010). According to China's agenda 21 of 1994 about two-thirds of cities in China depend on groundwater for urban water supply (Wu *et al.*, 2009). Despite having many surface water resources in Tanzania such as large freshwater lakes and rivers, groundwater has been playing crucial role in both domestic and irrigation supplies. The rural areas and major towns and municipalities in central and northern regions which are characterized by semi-arid climate depend largely on groundwater abstraction as the main source of water supply (Kashaigili, 2010; Taylor *et al.*, 2013). Arusha where the current study was conducted is one of the regions which depend largely on groundwater as the main source of water supply. Other regions include Dodoma, Singida and Kilimanjaro (Kashaigili, 2010). Despite the availability of groundwater potential, its quality which may be influenced by both natural and anthropogenic factors dictates the level of development and its uses.

Increasing groundwater exploitation has many side effects including groundwater storage depletion, land subsidence, salt water intrusion and general water quality degradation, and aquatic life distortion in riparian zones and wetlands. The impacts of groundwater over-abstraction may be minimized by a proper planning and rational utilization of the resource. Therefore, sustainable management of this resource is dependent on better knowledge of the groundwater recharge potential, abstraction rate and hydrogeochemical evolution. It should however, be noted that groundwater development in Arusha like many other places in Tanzania is not adequately controlled (Kashaigili, 2010; GITEC & WEMA, 2011; Mtoni *et al.*, 2013). In most cases, borehole drilling especially by private companies or individuals is carried out sometimes without getting permission from responsible water resources management authority as a result the amount of groundwater abstracted from the wellfield is not known. The practice has led into an alarming situation for those wells with some monitoring data. Among the reported issues are groundwater level decline and subsequent decrease in well discharges. The situation is likely to skyrocket the pumping costs as well as water scarcity due to rapid population growth accompanied by increase in socio economic activities which require more water. The situation if prolonged is expected to cause more serious effects not only in aquifers but also in wetlands, natural spring and river flows including aquatic ecosystem.

More than 400 wells (shallow and deep) have been drilled in the wellfield without proper planning and the abstracted groundwater amount is not known. Therefore, this study is aiming at establishing groundwater abstraction and water level (drawdown) trends from existing production wells as preliminary assessment for rational groundwater resource management. The study further aimed to determine the groundwater recharge and current abstraction impacts for sustainable water resource utilization.

4.2 Materials and Methods

4.2.1 Mapping of wells

The description of the study area is covered in chapter 3. Both individual and wells used for public water supply were considered in groundwater investigation (Fig. 18). During fieldwork that was conducted from 2015 to 2016, well mapping, discharge and drawdown measurements were carried out from existing production wells. Discharge and drawdown measurements could be possible only in wells used for public water supply. These wells were properly constructed and allow measurements of important hydraulic parameters for monitoring purposes which is not the case for individual owned wells. Apart from data collected during fieldwork, monitoring data for few wells from 2000 to 2014 were obtained from AUWSA and considered for groundwater investigation.

The data collected include lithology, well completion details and location coordinates using a hand-held global positioning system (GPS), GARMIN GPSmap62S. Addition list of well inventory conducted in 2013 in the study area were obtained from Pangani basin water office, a government agency responsible for water resources management at basin level. Most of these wells lacked almost all technical information such as hydrogeological aspect. However, the inventory provided other details such as type of well (deep or shallow), coordinates, operational status and intended use.

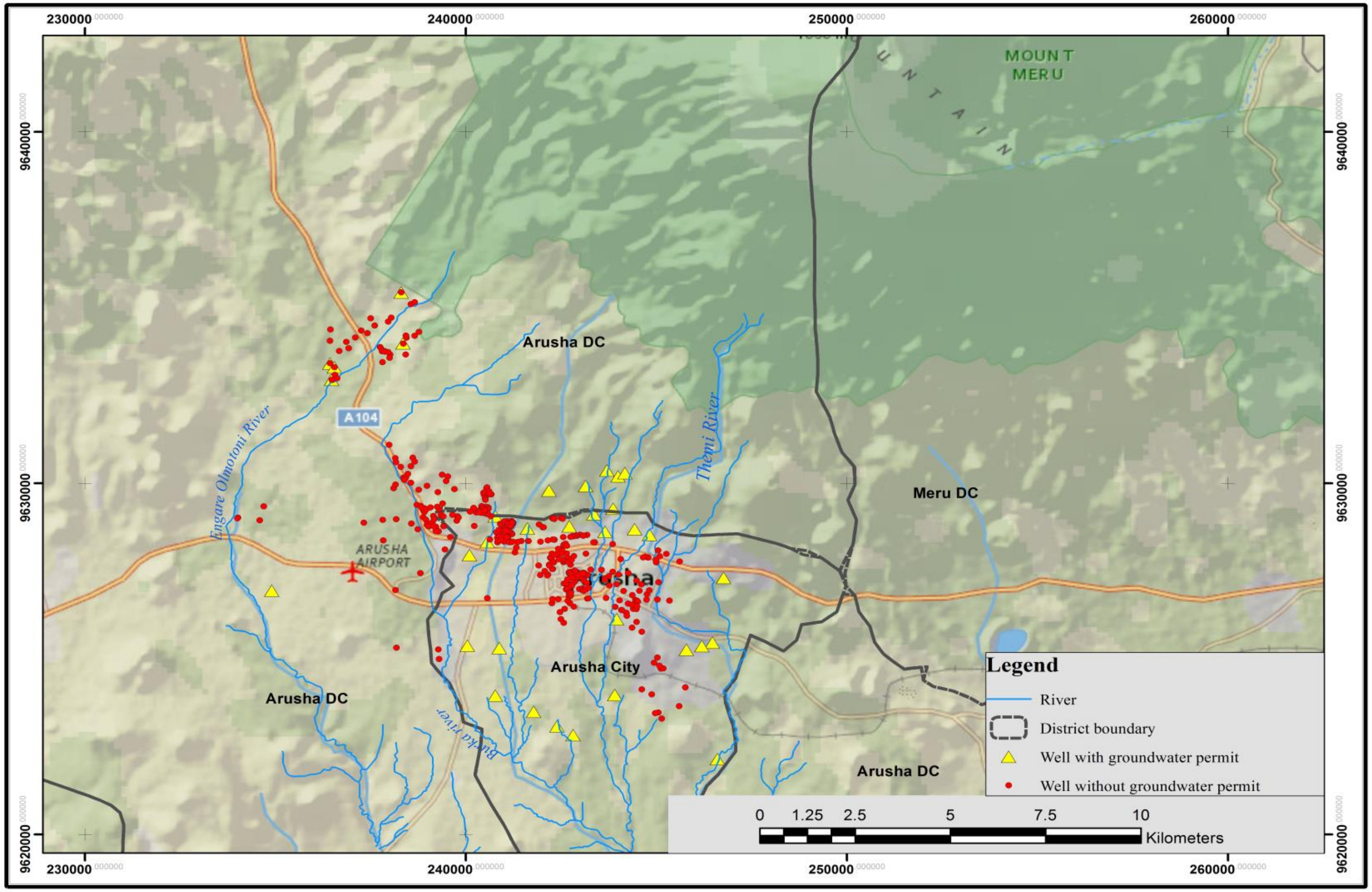

Figure 18: Groundwater development in Arusha wellfield

4.2.2 Well discharge measurements

Flow Meter, discharge measurements were obtained direct from the flow meter installed in well heads. The readings were taken every twenty four (24) hours or less whenever there was power interruption. When there was no power interruption, most of the wells used for public water supply were operated for 24 hours a day.

Indirect method, this approach was based on pumping rate and water consumption mainly governed by the use of water. The approach gave an average well discharge for a particular use. The pumping frequency was determined by available storage capacity and water consumption rate. For unknown pumping time, well discharge was estimated first by establishing water consumption for a particular use and respective storage period. In most cases, the storage volume or container was known as well as storage period. This method was applied to estimate well discharge for individual wells mainly owned by households, hotels, bars or restaurants, and car wash services.

4.2.3 Water level measurements

Drawdown measurements were possible only for wells with deeper line installation. The deeper line is installed inside the well casing to enable the water level meter into the well without being obstructed from electrical or other cables connected to the submersible pump. The drawdown readings were always taken while the pump was running as most wells operate for 24 hours a day. The water level was measured with reference from the ground surface in meters.

4.2.4 Groundwater recharge estimation

The groundwater recharge mechanism in the study area was considered to be due to direct infiltration from rainfall. The current study adopted the groundwater recharge rate (114.4 mm/year) established by GITEC & WEMA (2011) in a study titled “Groundwater assessment of the Pangani basin in Tanzania”. The recharge rate was calculated from the output of a computer-based Thornwaite Mather Water balance (TMWB) model. The TMWB model performs water balance problem based on long term average monthly precipitation, potential evapotranspiration, latitudes, soil properties and vegetation characteristics. In the study area, the recharge is likely to take place during long rains period starting from March to May where there is surplus for groundwater recharge.

4.3 Results

4.3.1 Mapping of wells

A total of 393 shallow and deep wells were considered in groundwater abstraction investigation in the study area (Fig. 18). Only 8% are registered and have water use permits which are statutorily issued by Ministry of Water through Pangani basin water board (PBWB). The rest of groundwater development and abstraction is carried out without following proper procedures as stipulated in Water Resources Management Act of 2009. Furthermore, those unregistered wells have no technical information documented to allow proper groundwater monitoring and management follow up.

4.3.2 Well discharge trend

Table 10 summarises well discharge data for thirteen (13) deep wells in Arusha wellfield from 2000 to 2016. A continuous decrease in well discharges has been observed in almost all wells in the wellfield (Figs. 19 through 28). Pumping has been conducted continuously and monitoring data could be obtained only from few production wells owned by AUWSA. The decrease in well discharge varies from one location to the other. The wellfield was divided into five different blocks based on the topography and proximity. The blocks and respective wells into brackets include Kiranyi (W15 and W18), Lorovani (W11 and W14), Sanawari (W07, W10 and W22) Ilboru (W12 and W19) and Emco (W04) (Fig. 9). In Kiranyi block, the discharge has declined for about 46% while in Sakina it has declined by 35% (Figs. 19 and 20) for the last seventeen (17) years period. In Lorovani block, two production wells were considered and observed to have a discharge drop of about 16% and 26% for Lorovani Bondeni (Fig. 21) and Lorovani yard (Fig. 22) respectively. This block was observed to experience less decrease in discharge compared to other blocks in the study area. Sanawari block that had three production wells showed a drop in well discharge of more than 50% for the last 17 years. Figures 23 through 25 show the decrease in well discharges of 27%, 50% and 57% for Sanawari P/S, Old Sanawari and Moivo II respectively. This block has recorded the highest discharge drop in the study area. The hydrographs in Ilboru block indicated abnormal trends and according to AUWSA personal communication (2015), the trend is probably due to power fluctuations (low voltage) and missing data in the area (Figs. 26 and 27). Emco is another block located in southern part of the study area and only single well had discharge records for consideration. Similarly, the well showed a discharge drop of about 19% (Fig. 28). Based on the spatial distribution of investigated wells and trends of well discharges, it is evident that groundwater reserve in Arusha city is continuously being depleted.

4.3.3 Water level trend

The drawdown measurements were only possible for three wells while others had no reliable data for consideration. The drawdown from Oltulelei well has increased from 100.3 to 113.8 m. This is a water level decline of about 11.9% (Fig. 29) for the past 16 years time period accompanied by decrease in well discharge of about 12.5% from 215 to 180 m^3/h (Table 10). Mianzini well which is also under the same block indicated water level decline of about 1.3 m for the measurements conducted between September 2015 and September 2016. The well lacks previous records which could be used to establish water level trends. Sanawari P/S well indicated 15.5 m water level decline (14.7%) since 2001 to date (Fig. 30). However, there is a missing data between 2010 and 2015. Other wells have neither records nor provision for taking drawdown measurements but they have significant decrease in discharges as shown in Table 10.

Table 10: Statistical summary of well discharge from 2000 to 2016 in the study area

				Discharge (m^3/h)						
Borehole	Constr. year	Depth (m)	N	Average	Min.	Max.	STDEV	Initial	Current (2016)	Decline (%)
Sakina	1978	91	66	25.7	19.5	36.2	3.3	30	23.6	35
Kiranyi	1997	189	60	52.6	32.5	76.6	11.0		41.3	46
Ilboru	1992	105	43	110.6	83.4	142.3	18.0	185	85.7	40
Oltulelei	1988	184	72	159.9	88.3	205.2	28.6	215	182.1	11
Mianzini	1988	142	41	40.2	29.6	49.4	5.3	85	35.4	28
Lorovan No. 4	1987	183	60	55.0	37.8	71.8	7.0	100	64.4	10
Lorovan Bondeni	1978	63	65	85.9	75.8	94.8	5.0	90	79.3	16
Lorovan Yard	1978	81	60	25.9	19.4	31.4	3.3	30	23.2	26
Sanawari P/S	1987	142	66	77.7	50.8	103.7	9.9	130	75.2	27
Old Sanawari	1978	88	62	31.6	15.3	50.4	9.1	42	25.4	50
Moivo II	1987	104	55	38.2	22.7	58.7	8.1	85	25.2	57
Sekei	1968	137	48	19.9	17.5	28.7	2.5	30	20.6*	28
Emco	1967	78	45	51.4	42.1	61.8	6.0	120	50.3*	19

N= number of measurements, * Measurements conducted between 2000 and 2010

Source: Routine records obtained from AUWSA

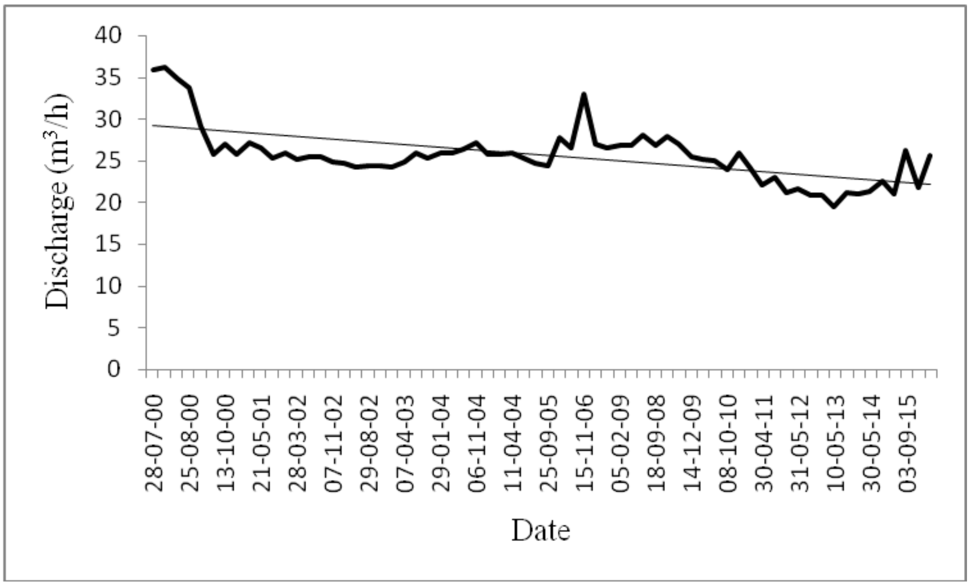

Figure 19: Groundwater hydrographs for Sakina borehole

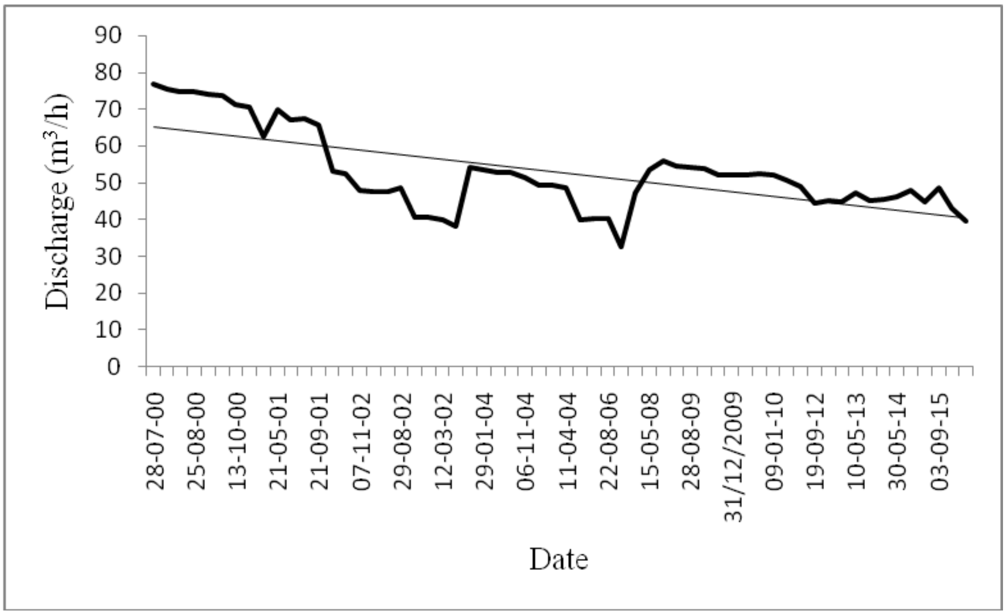

Figure 20: Groundwater hydrographs for Kiranyi borehole

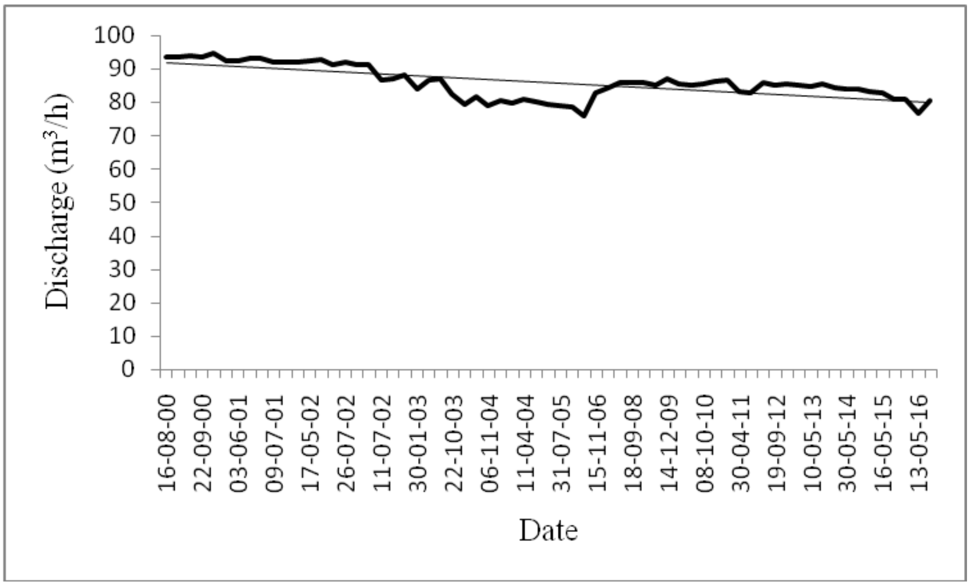

Figure 21: Groundwater hydrographs for Lorovani bondeni borehole

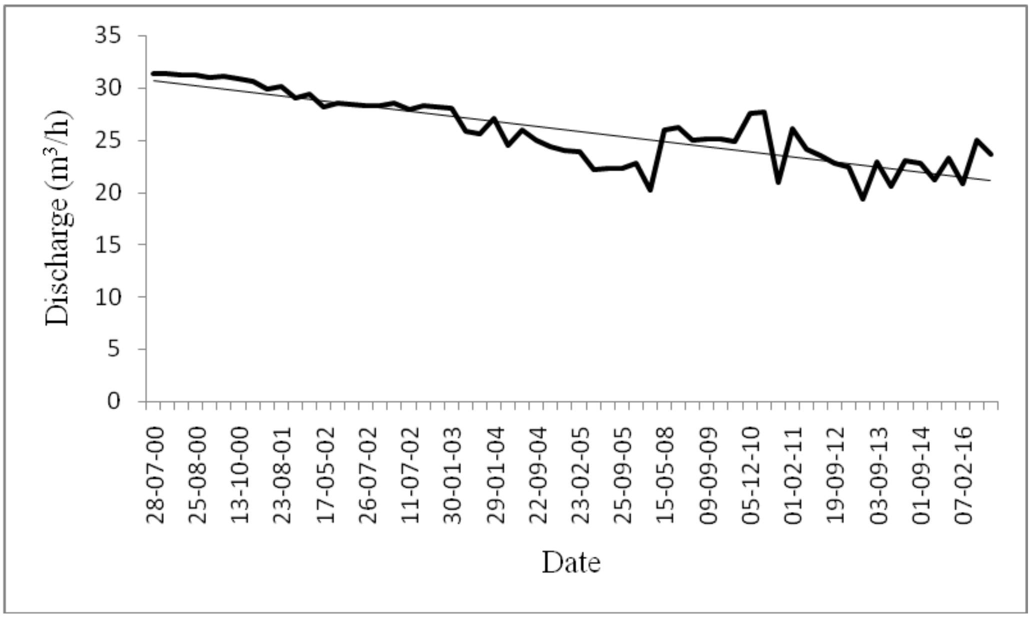

Figure 22: Groundwater hydrographs for Lorovani yard borehole

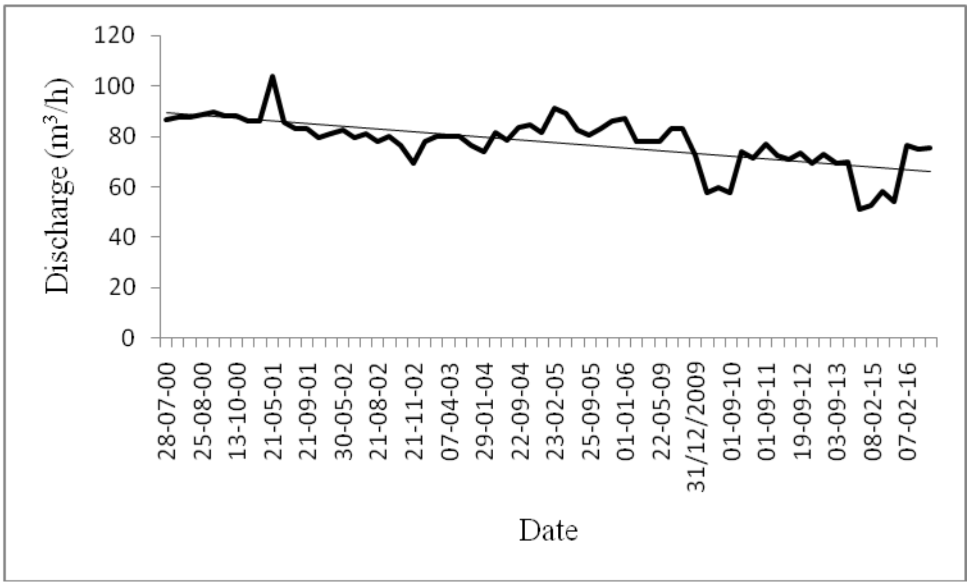

Figure 23: Groundwater hydrographs for Sanawari P/S borehole

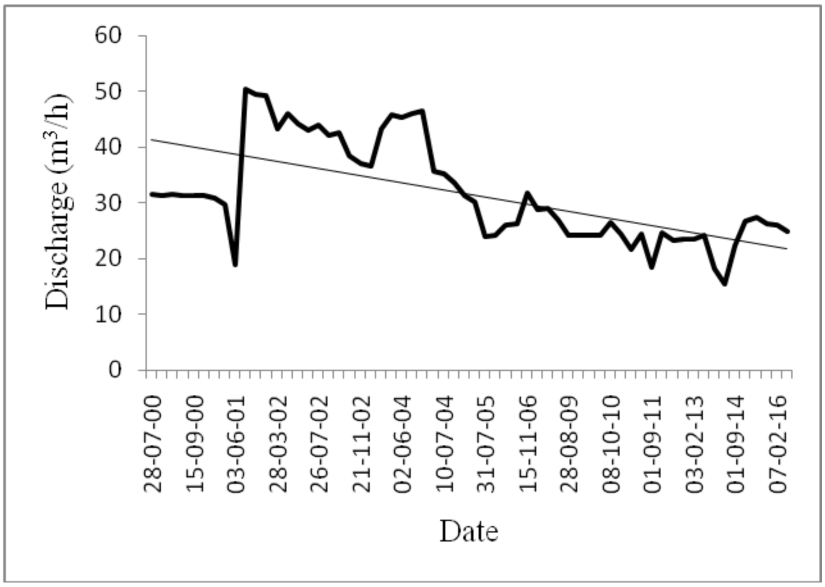

Figure 24: Groundwater hydrographs for Old Sanawari borehole

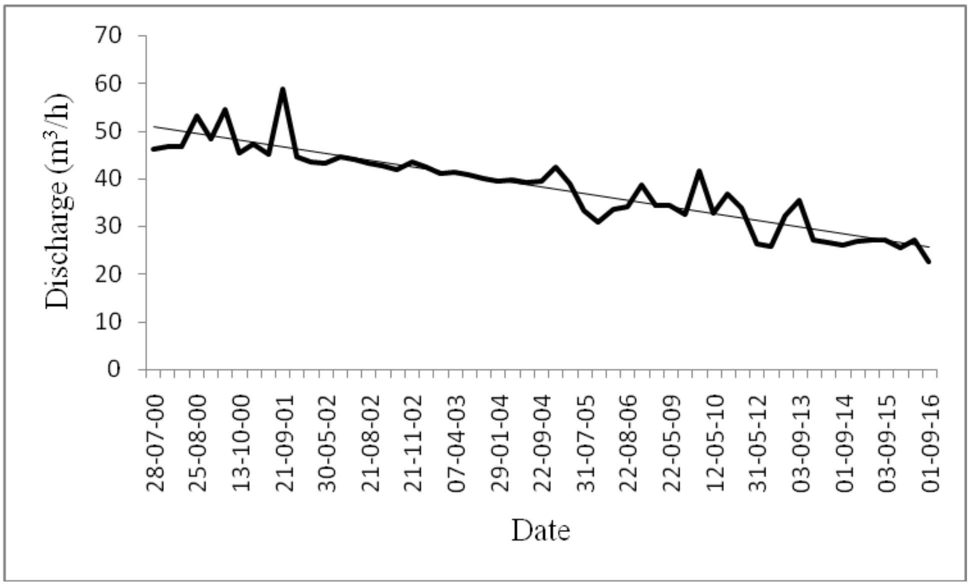

Figure 25: Groundwater hydrographs for Moivo II borehole

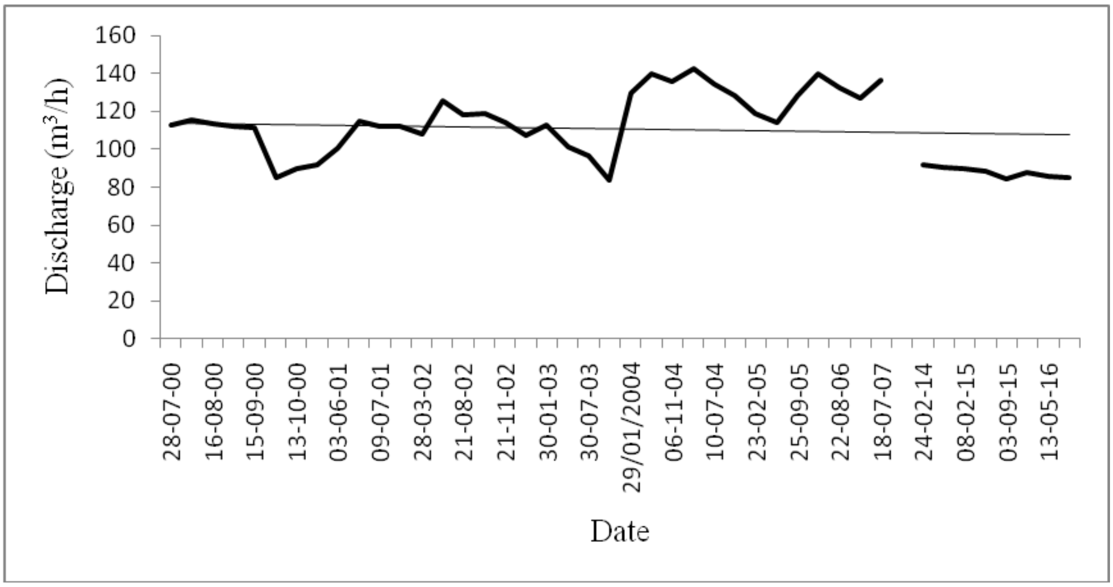

Figure 26: Groundwater hydrographs for Ilboru borehole

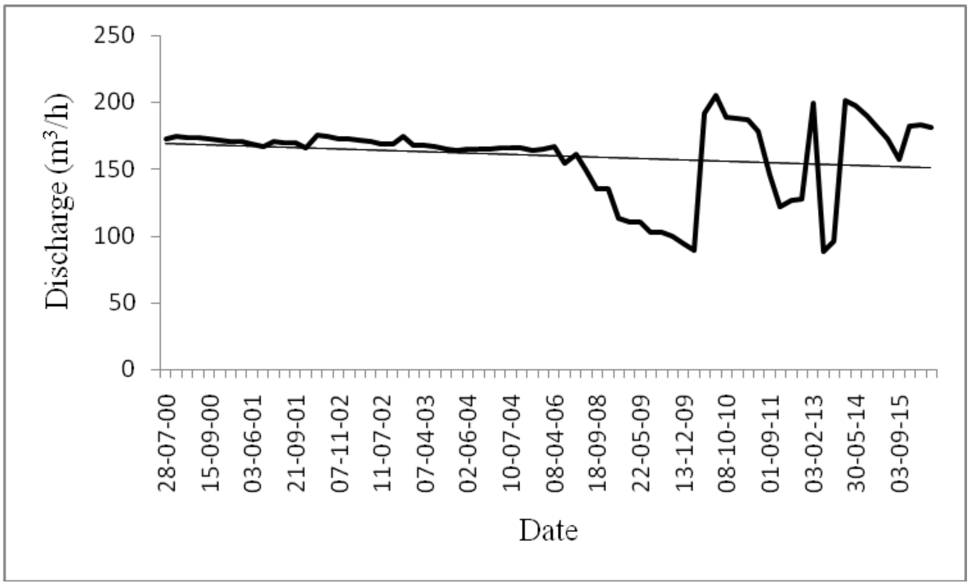

Figure 27: Groundwater hydrographs for Oltulelei borehole

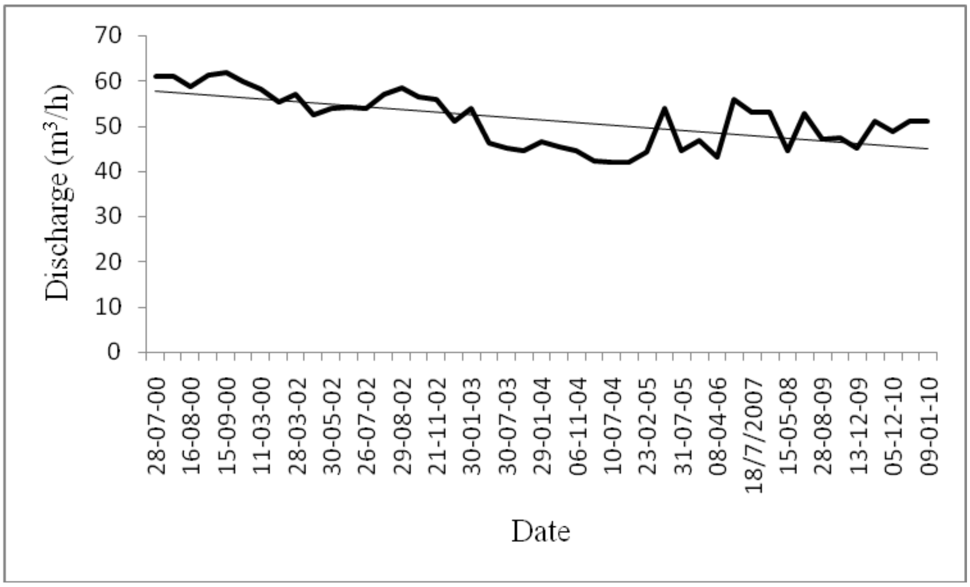

Figure 28: Groundwater hydrographs for Emco borehole

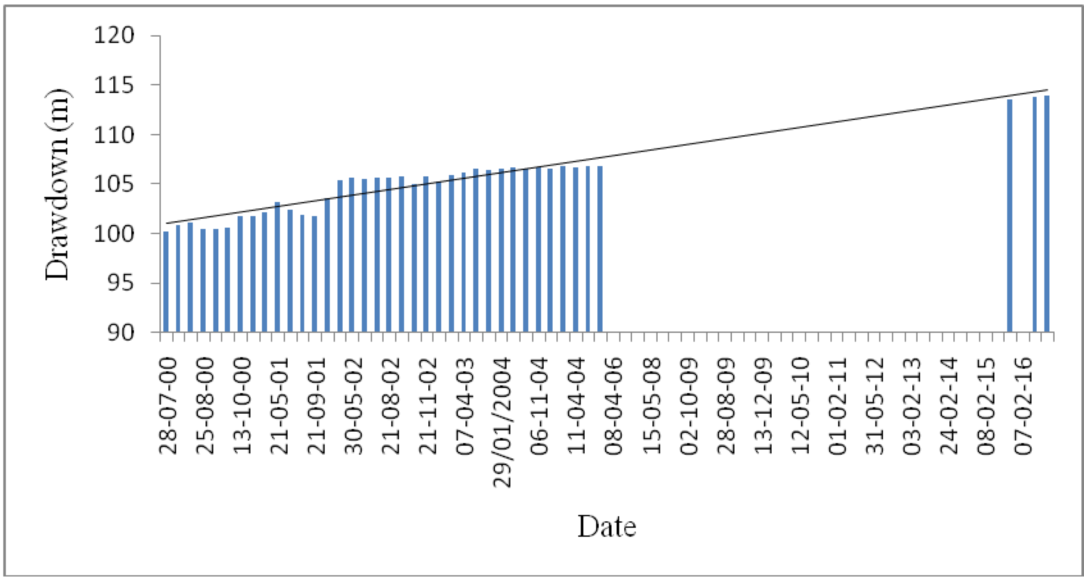

Figure 29: Oltulelei borehole water level changes over time

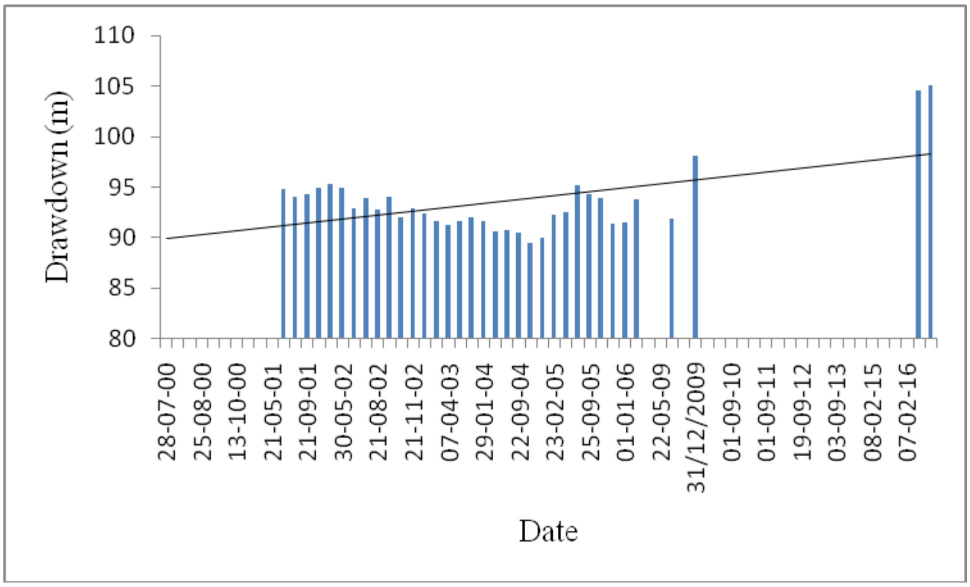

Figure 30: Sanawari P/S borehole water level changes over time

4.3.4 Groundwater abstraction

Domestic and commercial activities are among the main water users identified during field survey conducted to establish water abstraction for wells with no discharge and other technical information. The use and ownership of the wells varies from households, hotels, restaurants, bars and car wash service providers. The amount of groundwater abstracted for various uses is summarized in Tables 11-14. Table 14 shows amount of groundwater abstracted from deep wells. These are wells with known yields and discharges were directly read from flow meters. The wells are operated by AUWSA, water authorities responsible for public water supply in the city and its neighbourhoods. Almost all wells operate for twenty four (24) hours a day. However, due to power interruption pumping hours were approximated to 22 hours a day. The long pumping hours is due to high water demand in the city and insufficient storage reservoirs. The total amount of groundwater abstracted was estimated to 13 254 719 m^3/year (Tables 13 and 14). However, this may be less than the actual amount of groundwater abstracted from the wellfield as most private owned wells are drilled without getting permission from water resources management authority. Additionally, groundwater abstracted for irrigation including coffee and vegetable farming was not considered.

Table 11: Groundwater abstraction (estimated) for domestic use at household level

						Abstracted amount	
SN	Housing Unit (HU)	No. of person	Storage capacity (L)	Pumping Freq. (/d)	Storage period (d)	L/d	L/c/d
1	HU01	8	3000	1	4.0	750	94
2	HU02	8	3000	1	3.0	1000	125
3	HU03	5	3000	1	4.0	750	150
4	HU04	4	5000	1	5.0	1000	250
5	HU05	5	2000	1	3.5	571	114
6	HU06	6	3000	1	5.0	600	100
7	HU07	7	1000	1	1.0	1000	143
8	HU08	4	2000	1	5.0	400	100
9	HU09	5	4000	1	6.0	667	133
10	HU10	6	5000	1	5.0	1000	167
	Average	**5.8**				**774**	**138**

Table 12: Groundwater abstraction (estimated) for commercial use in Arusha city

SN	Sampling Location	Volume (L)	Pumping Time (h)	Pumping rate (L/h)	Pumping Freq. (/d)	Storage period (d)	Abstracted amount (L/d)	Abstracted amount (m^3/d)
	CAR WASH							
1	BPP	4000	2	2000	1	1	4000	4
2	LO	2000	0.4	5000	5	1	10000	10
3	CAP	20000	1	20000	1	2	10000	10
4	NJK	5000	2	2500	1	1	5000	5
	Average Abstraction						**7250**	**7.3**
	BAR/RESTAURANT							
1	ANP	9000	1	9000	2	1	18000	18
2	MST	15000	2	7500	1	1	15000	15
3	KGD	9000	2	4500	1	1	9000	9
4	PCN	7000	0.5	14000	2	1	14000	14
	Average Abstraction						**14000**	**14**
	HOTEL (normal) and LODGE							
1	IVR	3000	1	3000	2	1	6000	6
2	KTN	10000	4	2500	1	1	10000	10
3	AM	60000	6	10000	1	4	15000	15
4	PPH	15000	2	7500	1	1	15000	15
5	ANP	7000	1	7000	2	1	14000	14
	Average Abstraction						**12000**	**12**
	HOTEL (High Class)							
1	IMP	64000	4	16000	1	1	64000	64
2	NAS	56000	4	14000	1	1	56000	56
3	MTM	48000	4	12000	1	1	48000	48
4	NAH	32000	2	16000	1	1	32000	32
	Average Abstraction						**50000**	**50**

Table 13: Summary of estimated groundwater abstraction from existing private wells

SN	Category/Use	No. of Well	Unit abstraction (m^3/d)	Abstracted amount (m^3/d)	Abstracted amount (m^3/yr)
1	Domestic	262	0.8	210	76650
2	Hotel (High Class)	11	50.0	550	200750
3	Lodge/Hotel (normal)	89	12.0	1068	389820
4	Bar/Restaurant	33	14.0	462	168630
5	Car Wash	15	7.3	109	39785
	Total	**410**		**2392**	**875635**

Table 14: Groundwater abstraction (metered water) for public water supply in Arusha city

SN	Well ID	Coordinate		Depth (m)	Year	Abstracted amount		
		Northing	Easting			(m^3/h)	(m^3/d)	(m^3/yr)
1	AR/101	9627952	240096			14.0	308	112420
2	AR/444	9623975	243910	82	2011	24.0	528	192720
3	AR/106	9627309	246765	117	2010	12.0	264	96360
4	AR/103	9623080	242394	133	2010	8.0	176	64240
5	AR/102	9623499	241777	120	2010	4.0	88	32120
6	AR/104	9625313	240880	100	2010	16.0	352	128480
7	AR/486	9623955	240776	87	2010	18.0	396	144540
8	AR/105	9625264	245790	108	2010	8.0	176	64240
9	AR/MO	9633985	238356	65	2013	8.5	187	68255
10	BH-17	9622149	246603	73	2011	0.06	1.3	482
11	BH-19	9622833	242819	81	2012	4.6	101	36938
12	BH-18	9625380	240042	88	2012	42.6	938	342399
13	BH-14	9626129	243956	78	1967	51.4	1132	413088
14	BH-13	9628329	240563	91	1978	25.7	565	206105
15	BH-8	9629791	242180	184	1988	159.9	3517	1283861
16	BH-6	9629925	243147	105	1992	110.6	2433	888057
17	BH-5	9629123	243364	182		49.5	1089	397597
18	BH-9	9630364	243701	63	1978	85.9	1889	689614
19	BH-10	9630199	243998	81	1978	25.9	571	208321
20	BH-4	9630289	244177	183	1987	55.0	1209	441257
21	BH-1	9628693	244431	104	1987	38.2	841	306851
22	BH-15	9629060	240774	189	1997	52.6	1158	422528
23	BH-11	9629275	243868	88	1978	31.6	695	253691
24	BH-2	9628620	243656	142	1987	77.7	1708	623548
25	BH-7	9628774	242720	142	1988	40.2	885	322877
26	BH-16	9628710	241617	100	1986	12.1	266	97002
27	BH-12	9628533	244822	137	1968	19.9	438	159916
28	MGR/14	9626941	234906	134	2014	100.4	2209	806132
29	MNDL-1	9633405	236437	150		135.0	2970	1084050
30	MNDL-2	9633301	236553	120		128.0	2816	1027840
31	MNDL-3	9632943	236478	130		113.0	2486	907390
32	MSR	9635432	238304			45.0	990	361350
33	BIL04	9625465	246470			9.6	211	77088
34	BIL05	9625366	246196	110		15.0	330	120450
	TOTAL					**1541.9**	**33923**	**12381808**

4.3.5 Current water demand

Arusha city has households of different income as well as living standards ranging from lower to higher income. Estimation of water supply requirements or demand is governed by the living standard of the community and types of sanitation systems used. In case of Arusha city the medium income category was considered as an average representing majority of the city population. The common sanitation systems in the study area are septic tank connected to soak away pit, pour flush toilets and traditional pit latrines. Only small area (7 %) of the city is covered by sewerage network. Generally, the study area is considered as medium income area which requires 110 litres of water for every person per day (Table 15). Based on forecasted population to the year 2016 with annual growth rate of 2.7 % (URT, 2013), the population is about 845 030 inhabitants. This population requires about 92 953 300 l/d equivalent to 34x10^6 m^3/yr.

Table 15: Urban area water requirements (l/c/d)

Consumer category	FR	M-UT	M-PBT	Remarks
Low income using kiosks or public taps	25	25	25	Most squatter areas, to be taken as the minimum
Low income multiple household with Yard Tap	50	45	40	Low income group housing No inside installation and pit latrine
Low income, single household with Yard Tap	70	60	50	Low income group housing No inside installation and pit latrine
Medium Income Household	130	110	90	Medium income group housing, with sewer or septic tank
High Income Household	250	200	150	High income group housing, with sewer or septic tank

FR = flat rate, M-UT = metered with uniform tariff, M-PBT = metered with progressive tariff

Source: URT (2009)

4.3.6 Groundwater recharge

According to GITEC & WEMA (2011), the estimated annual recharge rate using Thornthwaite Monthly Water-Balance (TMWB) model is 114.4 mm. This information was derived from 40 years weather data collected in the study area. The potential groundwater recharge area is considered to be in high elevations on the slopes of Mt. Meru where faults and structures have been observed (Ghiglieri *et al.*, 2010). Figure 31 depicts delineated potential recharge area for Arusha wellfield which is estimated to 113.95 km^2. Only the area at the northern part of the study area located on the southern slopes of Mt. Meru was considered as it has been reported in previous works as potential recharge area in the region (Ghiglieri *et al*., 2008, 2010; Ong'or & Long-cang, 2007). The product of estimated recharge rate and potential recharge area of the wellfield gives a total annual recharge of 13 035 880 m^3/year. This excludes induced recharge from adjacent aquifers and nearby surface water bodies. Additionally, leakages from water supply networks and sewage disposal facilities may also contribute to groundwater recharge.

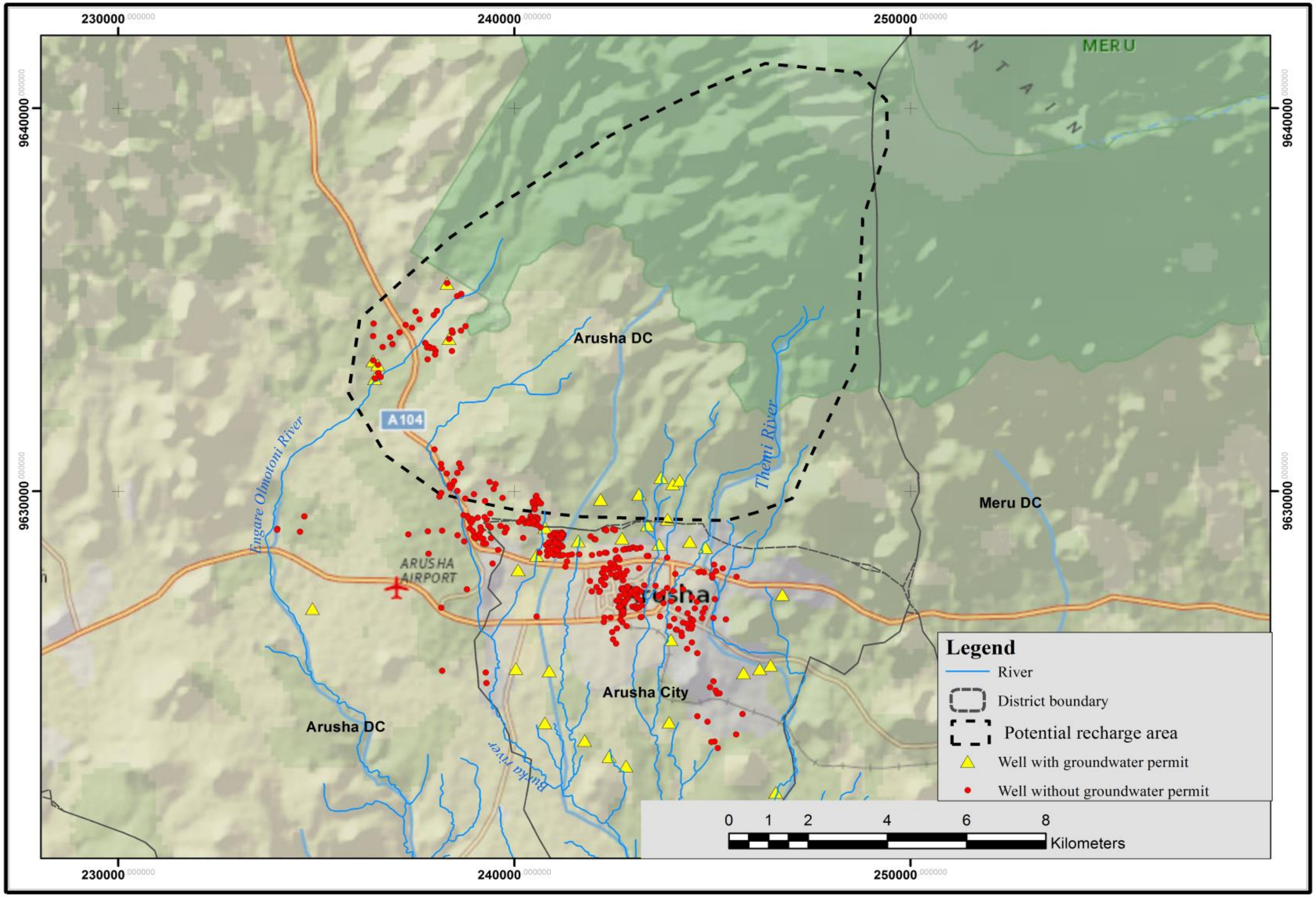

Figure 31: Potential groundwater recharge zone in the study area

4.4 Discussion and Conclusion

4.4.1 Groundwater depletion

Reduction in well discharge and subsequent decline in water level observed in the study area may result in various socio-economic and ecological effects. A decrease in well discharge ranging from 10 to 57% for a period not exceeding 17 years has been observed in different wells within the wellfield in the study area. Highly affected areas include those located in intense groundwater development zones. Figure 31 shows areas close to the city centre as well as along the main roads which are highly urbanised and have serious water storage depletion due to presence of numerous wells that have been developed without following proper procedures. The situation results into difficulty in the entire process of water resource management as the amount of groundwater abstracted from the wellfield is not even known.

The decrease in well discharge is also accompanied by increasing drawdown of more than 1.0 m per year which indicates a serious groundwater depletion problem in the study area. Similar impact has been reported in central Tanzania (Taylor *et al.*, 2013) and other many parts of the world which exceeds 1.0 m per year with extreme development conditions such as China, Spain and United States of America (Werner *et al.*, 2013; Famiglietti, 2014; Huang *et al.*, 2015; Custodio *et al.*, 2016; Kong *et al.*, 2016). In this study, wells located in areas with less groundwater development such as Lorovani and Ilboru (Figs. 21 and 26) indicated slightly decrease in discharge compared to areas with intense groundwater development (Fig. 31). Figure 32 also shows relatively high yields for deep wells and they are not affected much with over development.

Groundwater development effects have been reported in many parts of the world particularly those with intense development. These impacts include land subsidence, deterioration of groundwater dependent-ecosystem which include drying up of springs, wetlands and decrease in volume of surface water bodies (Liu *et al.*, 2011). Reduction in volume of surface water bodies happens in case a particular aquifer recharges the nearby streams or wetlands. In the study area, many rivers originate at high altitude as springs and as they continue flowing downstream more springs contribute further to increase in flow rates. If the current groundwater abstraction continues with increasing water supply demand due to rapid population growth, it is likely that most rivers and springs currently used for water supply will go dry or experience low flows. The situation of low flows has been experienced in some springs in the study area during dry months.

Despite all the illegal groundwater abstraction, it is therefore high time for water supply authority, water resources managers and the entire community in the study area to direct more efforts in exploring alternative water sources to cater for today and future demands. Among the possible alternatives to be considered is searching for new wellfield and rainwater harvesting. Water from alternative sources through blending can reduce the risks of using water with high fluoride concentration which commonly found in the study area.

In most hydrogeological settings, a change in water level in monitoring or production wells is a measure of change in groundwater storage in the respective aquifer. Increase in drawdown in some wells as revealed in this study suggests decrease in groundwater storage in Arusha well field. Thus, it is expected that the amount of water produced will not satisfy the current and future demand and pumping costs is going to shot up. Additionally, the decrease in groundwater storage in the aquifer is likely to induce change in water chemistry which determines the quality of groundwater for various uses. It is expected that over-abstraction could induce drawing water from adjacent aquifers which may not have water of good quality into the production wells. This may call for additional treatment costs or sometimes abandonment of a particular well. Such situation has been reported in the study area where one borehole at Ilboru Secondary school was abandoned due to increase in fluoride level after pumping for a couple of years (AUWSA personal communication, 2015).

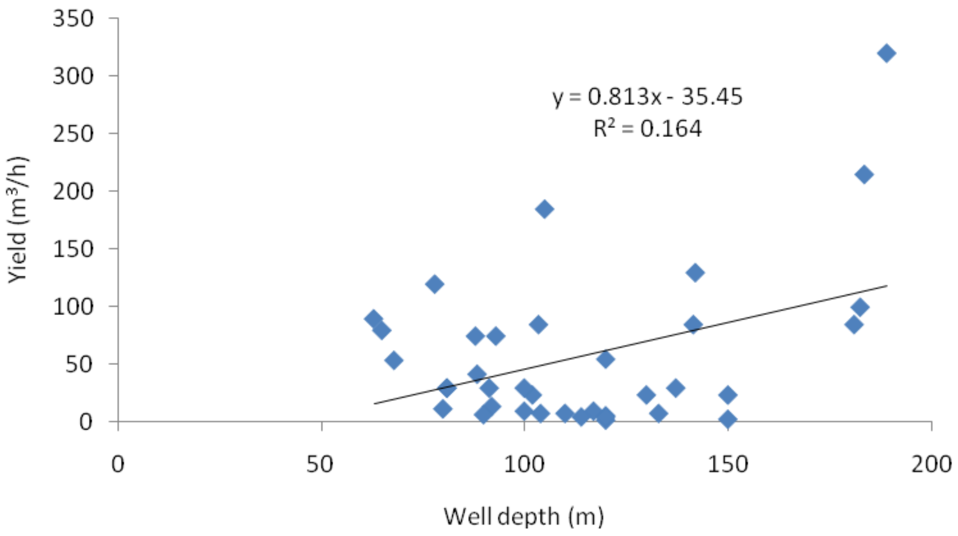

Figure 32: Scatter plot showing association between discharge with well depth

4.4.2 Groundwater recharge

Groundwater recharge due to precipitation infiltration in fractured or faulted formation is the dominant mechanism in the study area (Ghiglieri *et al.*, 2010). Annual recharge of about 114 mm has been estimated based on 40 years rainfall data in the study area. However, such a recharge mechanism is being affected by several factors which may lead into decrease in the estimated recharge amount. These factors include urbanization and climate change particularly temperature increase (Figs. 33 and 34) and decreasing trends of rainfall pattern (Figs. 35 through 38) which have already been experienced in Northern Tanzania. This trend agrees with the observation and prediction pointed out on climate change impacts in Tanzania (Omambia & Gu, 2010). This gives a bad signal to the sustainability of the Arusha wellfield as the demand for water supply is going up from year to year due to rapid population growth reported in the study area reaching 2.7% annually (URT, 2013).

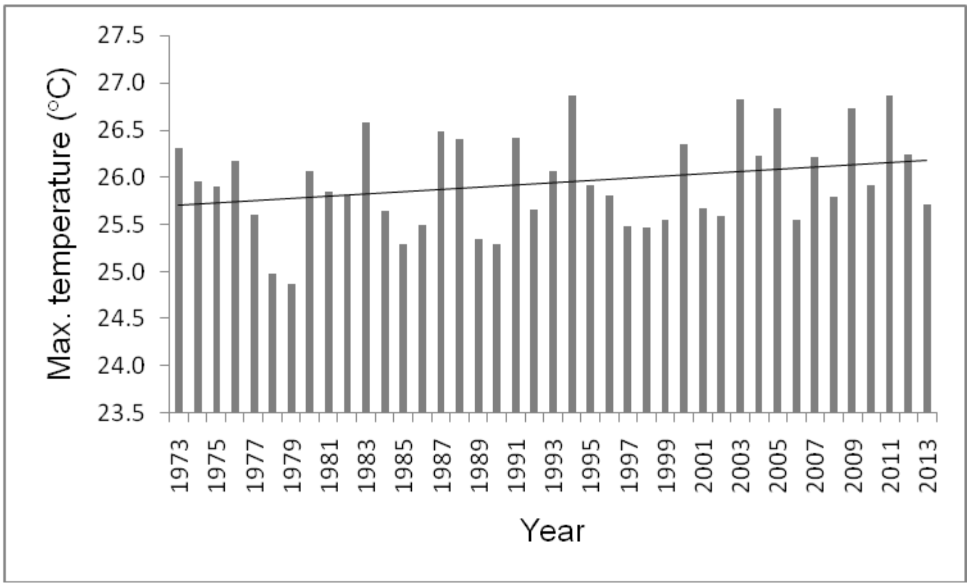

Figure 33: Average maximum temperature trend from 1973 to 2013, Arusha Airport MET station (TMA, 2013)

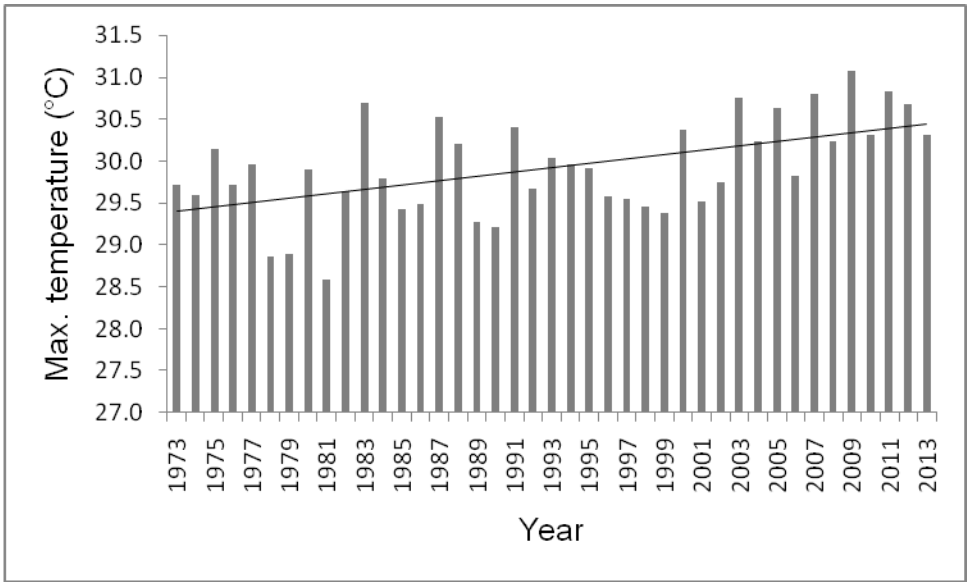

Figure 34: Average maximum temperature trend from 1973 to 2013, Kilimanjaro International Airport MET station (TMA, 2013)

The findings of this study (Chapter 5) has also revealed abstraction of relatively old groundwater (~ 1400 years BP) from deep wells which is quite long period of time for a depleted aquifer to replenish the abstracted water. Additionally, urbanization has been expanding towards the delineated recharge zone in the study area. This involves clearing of natural vegetation and increasing surface pavements and subsequently reduction in amount of rainfall infiltrating to the water table (Zipper *et al.*, 2017). However, in other hydrogeological settings it has been reported that urbanization increases groundwater recharge due to percolation from septic tank and soak away systems, reduced evapotranspiration as well as leakages from water and sewerage networks (Naik *et al.*, 2008; Tam & Nga, 2018; Wakode *et al.*, 2018). But this scenario depends mainly on geology and fundamental hydraulic structure and properties of the aquifer matrix in the area. Therefore, it is not guaranteed that the urbanization will counterbalance groundwater recharge due to rainfall infiltration especially in areas where recharge takes place in fractured and faulted formations like Arusha wellfield.

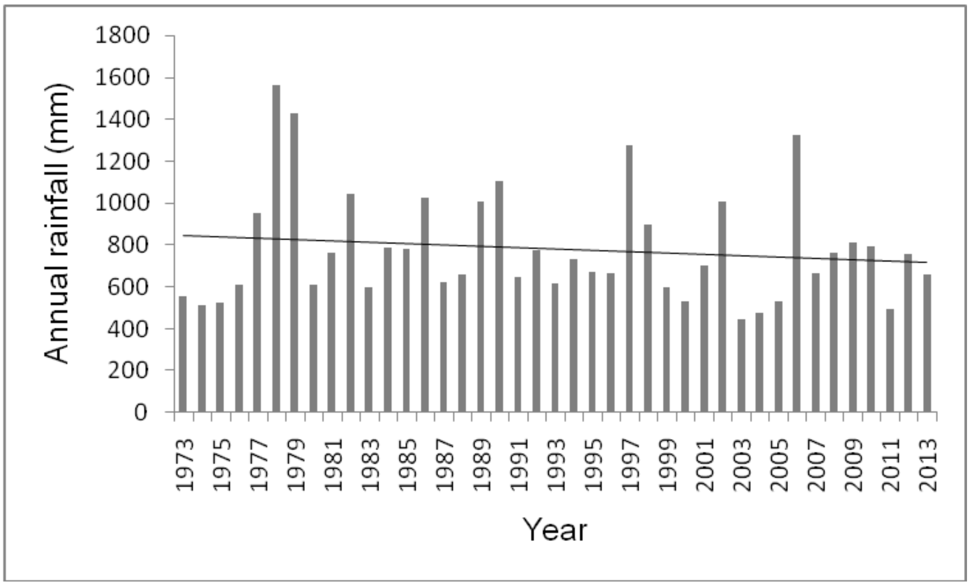

Figure 35: Annual rainfall trend from 1955 to 2013, Arusha Airport MET station (TMA, 2013)

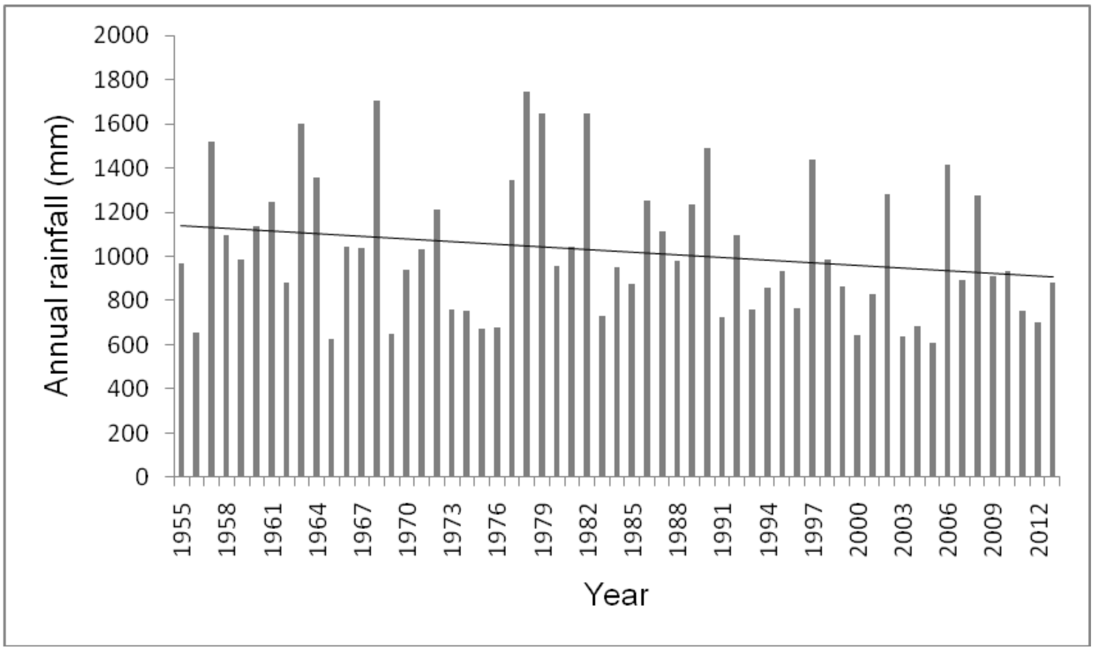

Figure 36: Annual rainfall trend from 1955 to 2013, Arusha Maji MET station (TMA, 2013)

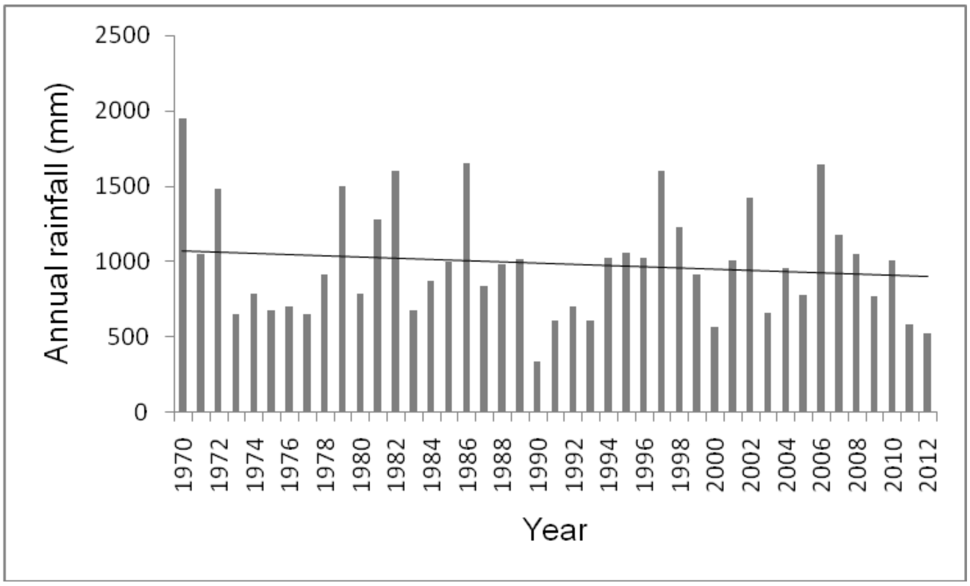

Figure 37: Annual rainfall trend from 1955 to 2013, Tengeru MET station (TMA, 2013)

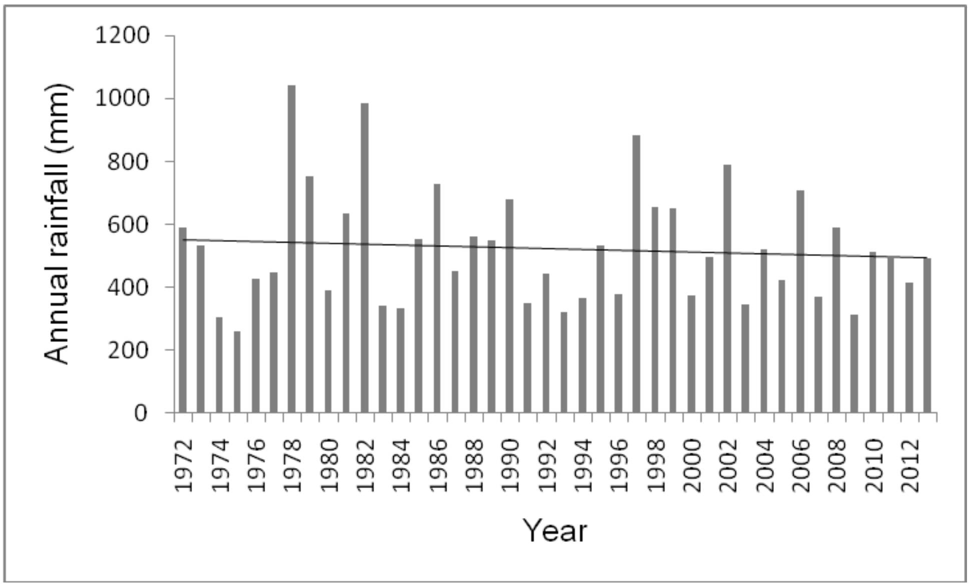

Figure 38: Annual rainfall trend from 1955 to 2013, Kilimanjaro International Airport MET station (TMA, 2013)

4.4.3 Groundwater abstraction and its impact

Groundwater development which doesn't follow or abides to the legal procedures in place is a threat to the sustainability of the Arusha wellfield. High water level decline and reduced in well discharge have been observed in most wells (Figs. 19 through 28) located in areas with intense groundwater abstraction. The amount of groundwater abstracted from more than 90% of the wells in the wellfield is unknown. The situation is accelerated by the rapid expansion of the city which doesn’t match with provision of water supply service. Thus, individuals are forced to drill their own wells sometimes without getting water use permit, the practice which poses a challenge of controlling the development of groundwater resource in the wellfield. To the moment it is still unclear the exactly amount of groundwater abstracted as only less than 10% of the wells have water use permit from water resources management authority. The permit specifies the use and amount of water abstracted from the wellfield which include drilled wells, springs and rivers. In addition, some individuals have established shallow dug wells (<15 m deep), this type of development is legally recognized and it is being conducted without having water use permit. However, the amount of water abstracted is also unknown as it depends on the intended use. Similarly, other individuals who are not supplied with water by AUWSA and have not opted for shallow or deep wells they use spring water for fulfilling their basic needs. Luckily, the area is blessed by having numerous springs with fresh water scattered all over the wellfield.

To this end, the current groundwater development in the area is likely to alter and affect the community welfare including groundwater-dependent ecosystems. Now, if the groundwater development continues with the current practice it will poses serious effects to the Arusha city. Some of the effects include drying up of springs which supply water to the community not covered by AUWSA. In addition, reduced spring or river flows will affect water-dependent ecosystem within and outside the study area particularly downstream of the catchment. Therefore, urgent management strategy is needed to rescue those impacts likely to occur as a result of groundwater over-abstraction in the wellfield and surrounding environments. The needed management strategy will have first to delineate the available water reserve with respect to present and future water demand for this new and fast growing touristic city and explore alternative water sources to supplement the already stressed wellfield. Currently, AUWSA is only able to produce and supply between 35 000 and 60 000 m^3/d of water which fluctuates seasonally but the current water demand is 93 000 m^3/d (AUWSA, 2014). Therefore, majority of the city and its neighbourhoods are not guaranteed to having safe drinking water instead they get water through their own effort and this encourages illegal groundwater abstraction hence makes groundwater management difficult.

4.5 Conclusion

The Arusha wellfield has been undergoing intensive groundwater development with abstraction in some cases taking place illegally. The illegal abstraction among other factors makes groundwater management a challenge in the wellfield. This study is only the first step towards a comprehensive effort to develop an effective groundwater management strategy for sustainable water resources utilization in the city and its neighbourhoods to meet the current and future water needs for socio-economic development as well as ecological functioning.

The findings of this study revealed significant groundwater reserve depletion in the wellfield. There is a water level decline of about 1.0 m per year. The decline is accompanied by reduction in well discharges of about 10 to 57% observed from existing production wells for a period not exceeding 17 years. The decline in water levels and subsequent reduction in discharges is a result of groundwater over-abstraction and reduced recharge in the area. More than 90% of individual wells are not registered and were drilled without getting water use permit from water resources management authority. Therefore, even the amount of groundwater abstracted is not known which makes a great challenge and difficult in managing this vital resource.

Areas with larger number of wells experience high level of decrease in well discharge compared to areas with small number of wells. Based on the available borehole data groundwater abstraction from Arusha wellfield was estimated to be 13 254 719 m^3/year. However, this amount is less than the actual amount of groundwater abstracted as most individual wells are drilled without getting water use permit from water resources management authority. Based on current population, water demand for the entire city and its neighbourhoods was estimated to 34 000 000 m^3/year which is more than twice the estimated groundwater abstraction from the wellfield. This suggests that majority of the residents are getting water outside the formal water supply system under AUWSA. The groundwater recharge was estimated to be 13 035 880 m^3/year which is less than both groundwater discharge from production wells and current water demand. This indicates that the wellfield is already stressed due to groundwater over-abstraction and calls for water managers to immediately consider alternative water sources for socio economic development of Arusha city.

The quality of groundwater notably level of fluoride has significantly increased in some production wells to the extent of abandoning them from public water supply system. Also some springs within the wellfield have experienced reduction in flows and they are likely to face further decrease if the current groundwater development practice continues. Additionally, there is evidence of decreasing rainfall amount in the region as a result of climate change which may contribute to reduced recharge and subsequently groundwater depletion. It is also anticipated that water level decline and subsequent reduction in well discharge will escalate the pumping costs due to increased distance from the water level to the ground surface.

CHAPTER FIVE

GROUNDWATER AGE DATING AND RECHARGE MECHANISM OF ARUSHA AQUIFER, NORTHERN TANZANIA: APPLICATION OF RADIOISOTOPE AND STABLE ISOTOPE TECHNIQUES[2]

Abstract

The continuous abstraction of groundwater from Arusha aquifers in northern Tanzania has resulted in a decline in water levels and subsequent yield reduction in most production wells. The situation is threatening sustainability of the aquifers and concise knowledge on the existing a groundwater challenge is of utmost importance. To gain such knowledge, stable isotopes of hydrogen and oxygen, and radiocarbon dating on dissolved inorganic carbon (DIC), were employed to establish groundwater mean residence time and recharge mechanism.^{14}C activity of DIC was measured in groundwater samples and corrected using a δ^{13}C mixing method prior to groundwater age dating. The results indicated that groundwater ranging from 1400 years BP to modern is being abstracted from deeper aquifers that are under intensive development. This implies that the groundwater system is continuously depleted due to over-pumping, as most of the sampled wells and springs revealed recently recharged groundwater. High ^{14}C activities observed in spring water (98.1±7.9 pMC) correspond with modern groundwater in the study area. The presence of modern groundwater suggests that shallow aquifers are actively recharged and respond positively to seasonal variations.

Key words: Groundwater age, radioisotopes, recharge mechanism, Tanzania

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[2] Hydrogeology Journal, https://doi.org/10.1007/s10040-018-1832-0

5.1 Introduction

In the city of Arusha, situated in northern Tanzania, groundwater abstracted through drilled wells and springs is the main source of drinking water supply (GITEC & WEMA, 2011). Most deep wells with large production volume are located in the central part of the study area near the foot of Mt. Meru at an elevation from 1400 to 1500 m above sea level (a.s.l.) (Ong'or & Long-cang, 2007). According to the Arusha Urban Water Supply and Sanitation Authority (AUWSA) medium-term strategic plan (2015-2020) report, springs contribute 45% of the daily water production whereas drilled wells and rivers contribute 37% and 18% respectively (AUWSA, 2014). However, the proportional contribution from each source varies depending on season of the year. The seasonal variations mainly affect springs and rivers by significant reduction in flows during dry periods but production from wells remains constant (AUWSA, 2014). Generally, water production fluctuates seasonally from an average of 35 000 m^3/d (dry season) to 60 000 m^3/d (rainy season) which is significantly low with respect to the current water demand (93 270 m^3/d) in the city (AUWSA, 2014).

Despite the lack of reliable information on the extent of groundwater abstraction, there is evidence of groundwater over-pumping in the study area. The decline of water levels (Table 16) and respective yield reduction (Table 17) in wells that have been operational for more than 20 years has been reported (Ong'or & Long-cang, 2007; GITEC & WEMA, 2011). Additionally, an inventory conducted by Pangani Basin Water Office (PBWO) in 2013 revealed more than 400 drilled wells in the study area, most of them unregistered by the responsible water resources management authority. This suggests that groundwater abstraction in the area is not adequately controlled to meet the needs of present and future use (Kashaigili, 2010; Van Camp *et al.*, 2014). However, aquifer storage may be affected by a number of factors other than groundwater over-pumping (Custodio, 2002). Natural phenomena, such as delayed and transient effects of the aquifer system, earth quakes, tectonic movement and climate change, have been reported in many parts of the world with significant effect in aquifer productivity (Custodio, 2002; Gorokhovich, 2005; Kitagawa *et al.*, 2006; Kløve *et al.*, 2014; Nigate *et al.*, 2017). Due to the complexity and dynamics of hydrogeological processes, knowledge of a particular aquifer system including recharge mechanisms and age of abstracted groundwater is required to inform the cause and extent of the existing problems. Such a situation leaves a number of questions with respect to sustainability of groundwater utilization in Arusha City for present and future water resources development and for avoidance of likely human impacts (drinking water supply) and ecosystem impacts (such as reduced stream flows and springs drying up and subsequent impacts on aquatic life). The current research was conducted to inform some of the existing problems or fill knowledge gaps in the study area. Among the issues addressed include whether groundwater storage depletion is caused by over-pumping or whether the aquifer system in the study area is not actively recharged.

In order to address some of the experienced groundwater challenges, the study employed the use of isotopic techniques to investigate the groundwater age and recharge mechanism in the study area. Currently, there are a number of tracers used for assessment of groundwater recharge and mean residence time (Chen *et al.*, 2011). These include chlorofluorocarbons (CFCs), tritium/helium ratio (^{3}H/^{3}He), krypton-85 (^{85}Kr) and carbon-14 (^{14}C) (Douglas *et al*. 2007; Hoque & Burgess 2012; Sigstedt *et al*. 2016). Chlorofluorocarbons (CFCs), ^{3}H/^{3}He and ^{85}Kr are mostly used for tracing young groundwater (< 100 years) (Szabo *et al.*, 1996; Mathouchanh and Aeschbach-Hertig, 2015). However, this study employed stable isotopes (hydrogen and oxygen), tritium and ^{14}C to meet its objectives. The ^{14}C technique uses the decay principle of the activity measured in dissolved inorganic carbon (DIC) to estimate the mean groundwater age of water travelling from the recharge zone to a discharge point along the flow path (Douglas *et al.*, 2007; Hagedorn, 2015). These techniques have been undergoing several improvements and are widely used in hydrogeological studies, particularly groundwater recharge and mean age estimation ranging from young (100 to 1000 years BP) to old groundwater (1000 to millions years) (Bakari *et al.*, 2012b, b; Stewart, 2012; Gleeson *et al.*, 2016). Despite wide acceptance and global application of isotope techniques, in Tanzania they have commonly been applied in geology and marine based sediments studies (Muzuka *et al.*, 2010; Muzuka *et al.*, 2004; Öberg *et al.*, 2013). Conventionally, many groundwater assessment studies have been focusing on quality issues and leaving aside aquifer sustainability in terms of potential recharge and groundwater mean residence time (Ghiglieri *et al.*, 2010; Ghiglieri *et al.*, 2012; Van Camp *et al.*, 2014; Malago *et al.*, 2017). Lack of such information is likely to threaten sustainability of aquifers under intensive development (Zongyu *et al.*, 2005).

Thus, this study aimed at establishing groundwater age and recharge mechanism for sustainable groundwater utilization in Arusha City, using ^{14}C, tritium and stable isotope (^{2}H and ^{18}O) techniques. Isotope composition data have been used for interpretation in conjunction with groundwater physical parameters and some hydrogeological information which were established during the borehole drilling and construction stage.

Table 16: Water level trends in the study area

Well details			Water level (year of measurement) (m b.g.l.)				
Location	Well ID	Well depth (m)	GE (1988)	HH (1994)	PBWO (2006)	GITEC (2011)	This work (2016)
Oltulelei	W12	184	36.95	58.90	58.90	-	113.77
Ilboru Sec	W19	105	9.88	17.50	17.50	24.26	-
Ilkloriti	W08	182	13.96	33.80	33.80	-	-
Moivo II	W09	104	2.27	16.60	16.60	27.30	73.43
Mianzini	W17	142	14.75	32.20	32.20	30.54	90.54

Abbreviations: GE-Gauff Engineers, HH-Howard Humphreys, PBWB-Pangani Basin Water Board. b.g.l. = below ground level

Source: GITEC and WEMA (2011)

Table 17: Well discharge trends over time in the study area

Well details		Discharge (year of measurement) (m^3/h)					
Location	Well ID	GE (1988)	HH (1994)	PBWO (2006)	WB (2010)	GITEC (2011)	This work (2016)
Oltulelei	W12	264	217.7	164.6	148.3	188.1	182.1
Ilboru Sec	W19	220	186.3	128.1	26.5	136	85.7
Ilkloriti	W08	150	84.5	-	-	52.2	34.6
Sanawari P/S	W10	160	-	-	91	75	75.2
Moivo II	W09	120	120	30.98	38.8	58.2	25.2
Mianzini	W17	80	63.9	48.2	49.4	49.4	33.6

Abbreviations: GE-Gauff Engineers, HH-Howard Humphreys, PBWB-Pangani Basin Water Board, WB-World Bank

Source: GITEC and WEMA (2011)

5.2 Materials and methods

5.2.1 Field work and groundwater sampling

Two categories of water samples were collected from the study area for different analyses. The first category was sampled from wells with depth ranging from 22 to 200 m below the ground surface. All wells considered in this study were tapping water at different depths depending on screen position and pump location (Appendix 2). The second category included samples from springs. Spring water samples were collected close to the point of discharge in order to minimize the effect of atmospheric contamination. Figure 39 shows the locations of sampling sites in the study area. All samples were collected in May 2016, which marked the end of the rainy season in the study area. The description of the study area including geological and hydrogeological settings is covered in chapter three.

Physical parameters such as pH, temperature and electrical conductivity (EC) were measured in situ using a multi-parameter meter (model HI 9828, Hanna Instruments) that was calibrated before use. The readings were taken after the instrument has stabilised. Alkalinity as bicarbonate (HCO_3^-) was determined in the laboratory immediately after sampling by an acid-titrimetric method using standard sulfuric acid and bromcresol green indicator for end-point detection (APHA, 2012).

A total of 25 samples were collected for both stable isotopes (^{18}O and ^{2}H) and radioisotopes analyses (^{14}C and ^{3}H). Six samples were from springs and the rest from boreholes. During field work, standard procedures and techniques for groundwater sampling and preservation detailed by Clark and Fritz (1997) were systematically applied prior to laboratory analyses.

High-density linear polyethylene (HDPE) sampling bottles were used to collect and store samples from taps located near the well heads. All boreholes used in this study were installed with electric submersible pumps which provide positive pressure systems with no atmospheric contact. Almost all samples from boreholes were collected after the pump had ran for at least six hours and in some cases it was found that pumps had been operating for more than a day non- stop for public water supply. This ensured that the water samples collected represent the aquifer formation being sampled and not stagnant water in the wells. All samples were kept in cool box and subsequently stored in a refrigerator (~4°C) after field work. Samples for stable isotopes analyses were sent to Stable Isotope Facility at University of California Davis, USA, whereas analyses of radioisotopes were carried out at Environmental Isotope Laboratory, University of Waterloo, Canada.

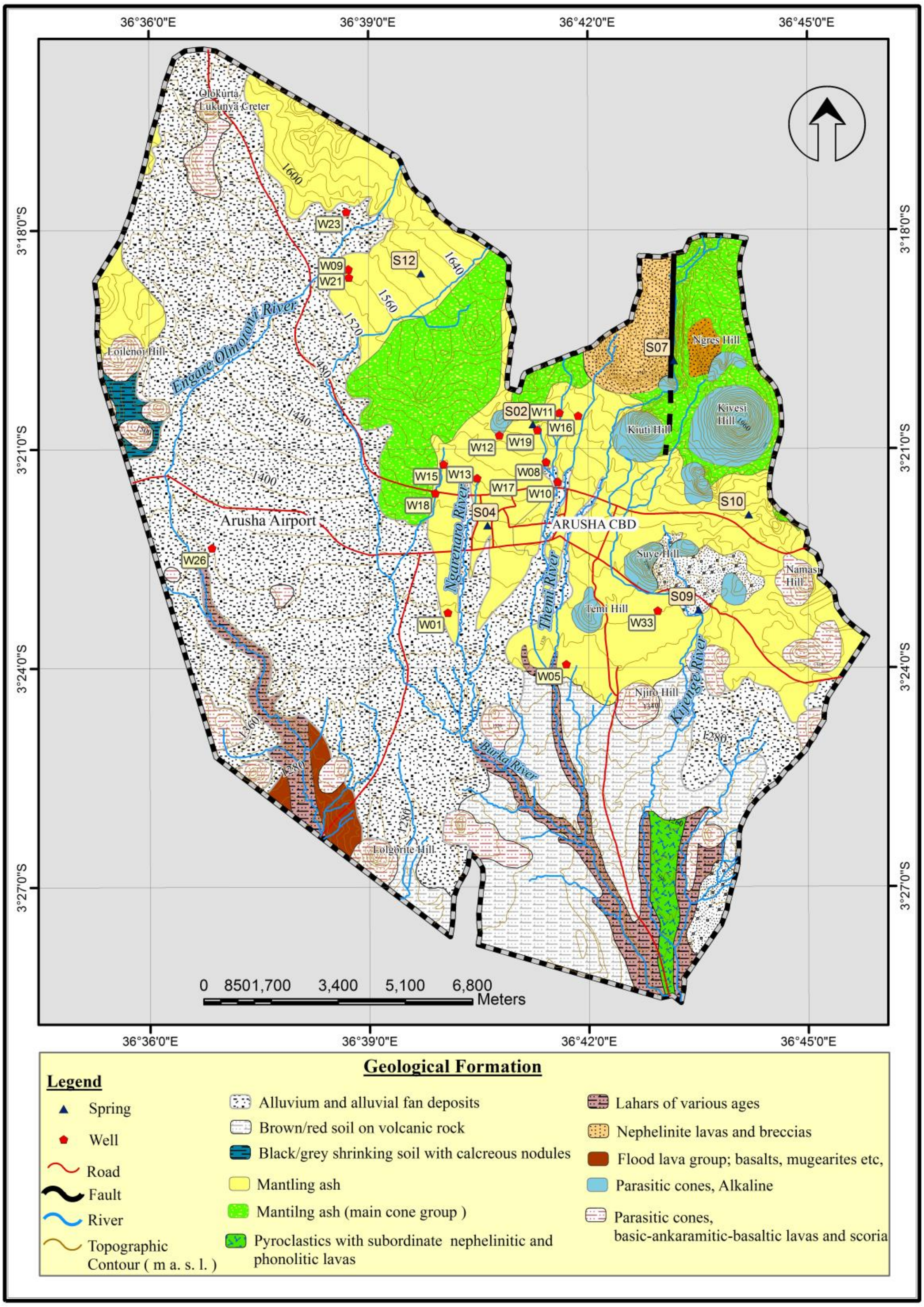


Figure 39: Hydrogeological map showing location of sampling sites (AA.VV., 1983)

5.2.2 Laboratory analyses

(i) Stable isotopes ($\delta^{18}O$ and $\delta^{2}H$) measurement

Simultaneous analysis of $\delta^{18}O$ and $\delta^{2}H$ isotopes in groundwater samples were carried out at Los Gatos Research, Inc., Mountain View, California, USA, using a Laser Water Isotope Analyzer V2. Sample isotope ratios were standardized using a range of working standards calibrated against Vienna Standard Mean Ocean Water (VSMOW) (Appendix 4). The isotope values of hydrogen and oxygen are reported in δ-notation relative to VSMOW (Eq. 1). The δ-values are expressed as parts per thousand or permil (‰).The precision for analyzed groundwater samples was ≤0.3‰ for $\delta^{18}O$ and ≤0.8‰ for $\delta^{2}H$. The average and standard deviation for an internal check dispersed throughout the run with known isotope ratio values for the calibrated water is given in Table 18.

$$\delta = (\frac{R_{\text{sample}}}{R_{\text{std}}} - 1) \times 1000 \qquad \text{(Eq. 1)}$$

where R_{sample} is $^{18}O/^{16}O$ or $^{2}H/^{1}H$ ratio of the water sample and R_{std} is for the standard in VSMOW.

Table 18: Mean and Standard deviation of water used for calibration

Measurable	**$\delta^{2}H$ (‰)**	**$\delta^{18}O$ (‰)**
Known value	-55.65	-8.04
Mean	-54.59	-7.79
n	7.00	7.00
1 standard deviation (SD)	0.60	0.15

(ii) Radioisotopes measurement

Tritium was determined by the direct tritium method with a precision of ±8 TU using a PerkinElmer LKB-WALLAC Quantulus 1220-002, USA (Appendix 5). The results are expressed as tritium units (TU) whereby 1 TU = 3.221 picocuries/L or 1 TU = 0.11919 Becquerels/L.

(iii) Carbon isotopes

The determination of $\delta^{13}C$ of dissolved inorganic carbon (DIC) was by mass spectrometry method using a Micromass PRISM-II, UK, 1990. The results are reported in δ values relative to Pee Dee Belemnite (PDB) standard with precision of ± 0.2‰. Radiocarbon (^{14}C) activity was determined using accelerator mass spectrometry (National Electrostatics Corporation 1.5SDH-1 Pelletron Accelerator). The results are reported in percent modern carbon (pMC) with precision of ± 0.3. According to Clark and Fritz (1997), the activity of modern carbon represents 95% of the ^{14}C activity in 1950 of the NBS oxalic acid standard equivalent to the activity of the wood grown in 1890 in a fossil CO_2-free environment. For the purpose of age dating, the measured ^{14}C activity values were normalized to values corresponding to $\delta^{13}C$ -25‰ to account for sample background contamination during the process of graphitization.

5.2.3 Groundwater age dating and ^{14}C correction methods

The groundwater age dating by ^{14}C is governed by the principle of radioactive decay given by Eq. 2. The normalized ^{14}C activity was applied together with initial ^{14}C activity of DIC in the recharge area for each sample to estimate the respective groundwater ages. Groundwater radiocarbon age was expressed as years before present (BP).

$$A = A_o e^{-\lambda t} \qquad \text{(Eq. 2)}$$

where t is the mean residence time from recharge to discharge point in years, A is the measured ^{14}C activity of DIC in the sample expressed in pMC, while A_o is the initial ^{14}C activity in the recharge, λ is the decay constant which equals $\ln 2/T_{1/2}$, and $T_{1/2}$ is the ^{14}C half life (5730 years).

Radiocarbon ages were determined from the measured ^{14}C activities. The first approach which is shown in third column (Table 20) assumed that no dilution occur other than natural decay of ^{14}C. This assumption is commonly applied in groundwater age interpretation particularly in basaltic formations characterized by lack of organic carbon which may contain minor amounts of calcite in vesicles. This was reported by Bosworth (1989), cited by Raiber *et al.* (2015). The initial ^{14}C activity is assumed to be 100 pMC which gives uncorrected ages; however, this assumption ignores any subsequent geochemical reactions from the point of groundwater recharge and along the flow path. Due to the complexity of the geochemical reactions and unidentified sources of carbon in the aquifer system, it is always necessary to correct radiocarbon ages for addressing any possible dilution effects from both known and uncertain sources (Clark & Fritz, 1997). There are several existing age correction techniques applied in different environmental conditions depending on available data. This work applied the statistical correction (Vogel, 1970) and δ^{13}C mixing method (Pearson & Hanshaw, 1970) for ^{14}C age correction. The δ^{13}C mixing method indirectly accounts for carbon chemistry in terms of mixing of different components. Apart from mixing, the process includes an isotope exchange process which is considered as a simple addition of one of the two components, CO_2 or solid carbonate, into the mixing (Fontes & Garnier, 1979). Fontes and Garnier (1979) concluded that the Pearson method provides good approximation to the initial ^{14}C activity of the total dissolved carbon with respect to their new approach. The initial activity of the total dissolved carbon is estimated based on the ^{13}C content of each species (Clark & Fritz, 1997). The correction factor (q) is given by:

$$q = \frac{\delta^{13}\mathrm{C}_{\mathrm{DIC}} - \delta^{13}\mathrm{C}_{\mathrm{carb}}}{\delta^{13}\mathrm{C}_{\mathrm{rech}} - \delta^{13}\mathrm{C}_{\mathrm{carb}}} \qquad \text{(Eq. 3)}$$

where: $\delta^{13}C_{DIC}$ = measured ^{13}C in groundwater

$\delta^{13}C_{rech}$ = δ^{13}C value for DIC in the infiltrating groundwater

$\delta^{13}C_{carb}$ = δ^{13}C of the calcite being dissolved

In this work, the values of $\delta^{13}C_{rech}$ and $\delta^{13}C_{carb}$ were opted to be -23‰ and 0‰ (Clark & Fritz, 1997)

The statistical correction method as described by Vogel uses initial ^{14}C activity of 85% of the modern carbon (Vogel, 1970). However, this approach gives ages which are probably too old and does not account for the occurrence of recent waters in the recharge area (Fontes & Garnier, 1979).

5.3 Results

5.3.1 Stable isotopes and tritium

Results of stable isotopes of hydrogen and oxygen (Table 19) plotted above and parallel to both East African local meteoric water lines (LMWLs) and the global meteoric water line (GMWL) (Fig. 40). The GMWL ($\delta^2H = 8.13\delta^{18}O + 10.8$) is based on the refined Craig's line (Clark & Fritz, 1997) whereas the LMWL for Dar es Salaam, Tanzania ($\delta^2H = 7.01\delta^{18}O + 6.83$) and for Entebe, Uganda ($\delta^2H = 7.38\delta^{18}O + 10.78$), are reported (Rozanski *et al.*, 1996). The best fit line for the analyzed stable isotopes is $\delta^2H = 6.7\delta^{18}O + 9.8$. Water samples from springs had δ^2H values that ranged from -24.8 to -18.5‰ VSMOW while samples of δ^{18}O ranged from -5.1 to -4.1‰ VSMOW. In samples from wells, δ^{2}H varied from -26.1 to -17.0‰ while δ^{18}O ranged from -5.34 to -4.32‰. The results indicate that spring water is more enriched in ^{18}O and ^{2}H compared to deep groundwater samples. The deuterium excess, $d = \delta^{2}H - 8\delta^{18}O$ is considered as a measure of the relative proportions of the sample and an index of deviation from the GMWL (Dansgaard, 1964). The deuterium excess varied from 13 to 18‰ for the analyzed groundwater samples. All samples were also analyzed for tritium content however the results were less than analytical detection limit (6.0 TU) for all samples.

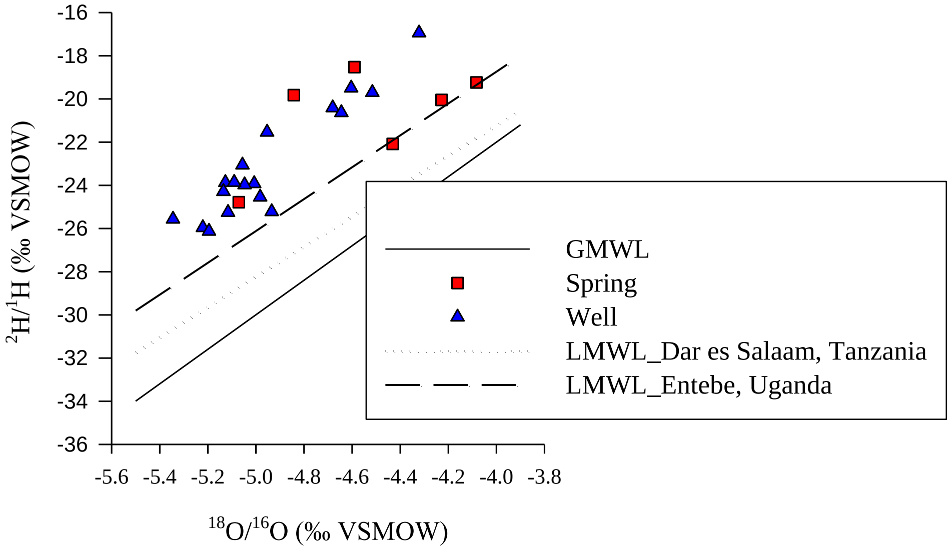


Figure 40: Stable isotope signatures of groundwater in the study area

Table 19: Physical-chemical and isotopic characteristics of groundwater in the study area

Location Name	**SID**	**Depth**	**Pump Posit.**	**Altitude**	**EC**	**HCO^{3-}**	**pH**	**δ^2H**	**$\delta^{18}O$**	**d-excess**	**$\delta^{13}C$**	**^{14}C**		**^{3}H**	
		(m)	(m b.g.l.)	(m a.s.l.)	(µS/cm)	(mg/L)		(‰ VSMOW)	(‰ VSMOW)	‰ VSMOW	± 0.2‰ (PDB)	(pMC)	1σ error	±8.0 (TU)	1σ error
Rainwater	-	-	-	-	21.3	4	6.2	20.2	-0.10	20.99	-	-	-	<6.0	1.76
Ilboru Sec	S02	-	-	1479	311	243	7.03	-19.2	-4.1	13.42	-14.1	106.20	-	<6.0	1.73
Engarendolu	S04	-	-	1406	671	280	6.56	-20.0	-4.2	13.77	-11.9	101.80	-	<6.0	1.68
Masama Kati	S07	-	-	1582	162	160	7.83	-22.1	-4.4	13.36	-14.4	100.71	-	<6.0	1.73
Machare	S09	-	-	1286	350	268	6.42	-18.5	-4.6	18.19	-14.9	103.60	-	<6.0	1.74
Baraa	S10	-	-	1429	209	216	6.76	-19.8	-4.84	18.91	-14.56	87.40	0.44	<6.0	1.72
Njoro	S12	-	-	1601	376	190	7.67	-24.8	-5.07	15.78	-12.49	89.04	0.31	<6.0	1.71
Sombetini Sec	W01	100	-	1348	601	188	7.18	-23.9	-5.01	16.13	-	-	-	-	-
Lemara P/S	W05	22.5	-	1322	640	270	6.59	-19.7	-4.52	16.42	-	-	-	-	-
Ilkloriti	W08	68	-	1463	362	238	7.50	-21.5	-4.95	18.09	-14.07	61.36	0.24	<6.0	1.68
Moivo II	W09	103.5	85	1556	369	208	7.89	-19.5	-4.60	17.33	-15.60	70.95	0.25	<6.0	1.67
Sanawari P/S	W10	142	125	1433	380	223	7.94	-20.4	-4.68	17.02	-15.06	61.73	0.27	<6.0	1.69
Lvani Bondeni	W11	63	-	1511	328	205	7.71	-23.9	-5.13	17.14	-14.08	61.87	0.26	<6.0	1.69
Oltulelei	W12	183.5	157	1509	382	211	7.12	-25.6	-5.34	17.19	-13.74	82.53	0.31	<6.0	1.79
Ilkiurei	W13	100	-	1435	494	215	7.84	-24.3	-5.14	16.79	-	-	-	-	-
Kiranyi	W15	189	-	1431	468	254	7.37	-25.3	-5.12	15.67	-	-	-	-	-
Lorovani No. 4	W16	182.5	172	1510	304	260	7.60	-20.6	-4.64	16.52	-14.73	68.51	0.31	<6.0	1.71
Mianzini	W17	141.5	121	1452	433	230	8.27	-24.0	-5.05	16.40	-13.65	66.58	0.43	<6.0	1.73
Sakina	W18	91.4	-	1412	456	210	7.56	-26.0	-5.22	15.81	-	-	-	-	-
Iliboru Sec	W19	105	102	1501	385	225	7.95	-23.9	-5.09	16.86	-13.44	49.49	0.25	<6.0	1.75
Moilo	W21	65	62	1560	560	280	7.98	-26.1	-5.19	15.43	-10.56	79.05	0.27	<6.0	1.65
Missiori	W23	-	-	1589	956	250	7.54	-25.2	-4.93	14.25	-9.81	92.56	0.31	<6.0	1.73
Mnadani No.3	W25	130	-	1488	962	270	8.43	-24.5	-4.98	15.31	-9.83	89.75	0.23	<6.0	1.77
Magereza	W26	134	-	1371	1073	350	7.40	-23.1	-5.06	17.38	-8.30	64.20	0.25	<6.0	1.74
Banana No.5	W33	110	87	1353	571	346	6.85	-17.0	-4.32	17.62	-13.57	107.00	-	<6.0	1.69

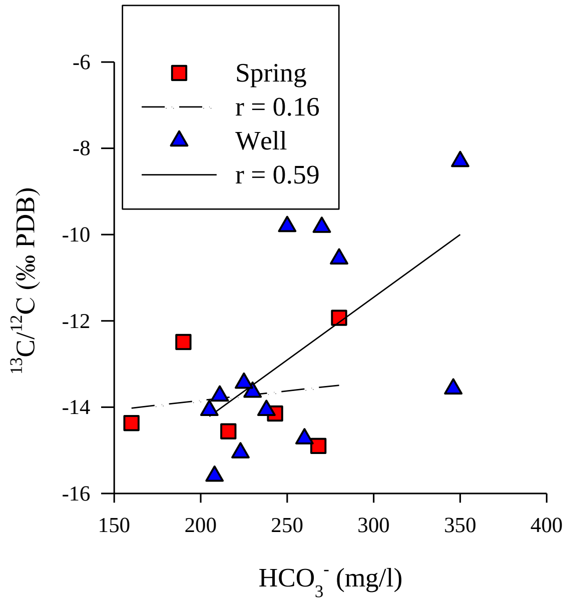
Abbreviations: SID – sample ID (S=spring, W=well), b.g.l. – below ground level, a.s.l. – above sea level, EC – electrical conductivity, d-excess – deuterium excess, VSMOW – Vienna Standard Mean Ocean Water, PDB – Pee Dee Belemnite, pMC – percent modern carbon, BP – before present, RC – radio carbon.

5.3.2 ^{14}C and ^{13}C of Dissolved inorganic carbon (DIC)

The values of the stable carbon isotope, δ^{13}C, varied from -14.9 to -11.9‰ PDB in spring water while in well water the values ranged from -15.6 to -8.3‰ PDB. Depending on the prevailing pH condition, δ^{13}C values are higher as water infiltrates through the soil matrix, signifying enrichment (Clark & Fritz, 1997). The values of δ^{13}C correlated positively with bicarbonate HCO_3^- (r = 0.597 (n=13), p<0.01) and EC (r = 0.926 (n=13), p<0.01) for well samples; however, groundwater sampled from springs showed weak correlation with respect to HCO_3^- (Fig. 41). The bicarbonate is mainly formed as water dissolves soil carbon dioxide during the infiltration process. Enrichment with δ^{13}C has been observed more in well water samples than springs (Table 19). Low values of EC (347±179 µS/cm) were observed in springs compared to well waters (540±232 µS/cm) with the exception of spring S04 (671 µS/cm) which is located in the city center.

Measured ^{14}C activities of water samples varied from modern in spring water (87.00–106.20 pMC) to low values (49.49–92.56 pMC) corresponding to great age in well water samples (Table 19). The high values of ^{14}C activity observed in spring water imply modern groundwater. Samples from wells had relatively low values of ^{14}C activity which indicates longer mean residence times. ^{14}C activities correlated positively (r = 0.49 (n=12), p<0.01) with altitude in samples collected from wells (Fig. 42). In addition, samples with higher ^{14}C activities were relatively enriched in both ^{2}H and ^{18}O (Fig. 43).

(a)



(b)

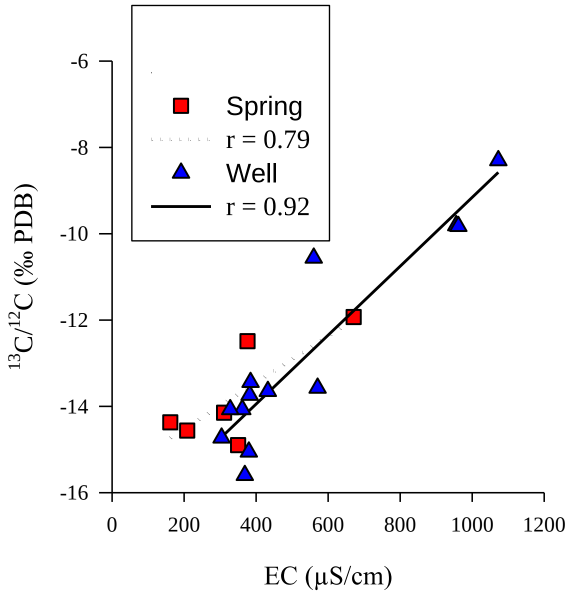


Figure 41: Scatter plot for $\delta^{13}C$ with (a) bicarbonate and (b) electrical conductivity in water samples

5.3.3 Groundwater age

Radiocarbon dating revealed that groundwater in the study area was recharged in the Quaternary period during late Holocene. The groundwater ages determined based on corrected ^{14}C activity ranged from 1400 years BP to modern age. All spring water samples fell under modern groundwater, however samples S10 and S12 were observed to have relatively lower ^{14}C activities compared to others (Table 20). However, samples from wells of different depths had groundwater ages ranging from 1400 to 100 years BP. The ^{14}C activities (directly related to estimated groundwater ages) were positively correlated (r = 0.49) with altitude but no clear trends were observed with well depth (Fig. 42). Young groundwater was observed in most wells located at high altitude and vice versa.

Table 20: Groundwater ^{14}C ages rounded to the nearest 10^2 years

			Uncorrected age	Corrected age	
Location Name	SID	^{14}C (pMC)		Vogel model (1970)	Pearson model (1970)
Ilboru sec	S02	106.2	Modern	Modern	Modern
Engarendolu	S04	101.8	Modern	Modern	Modern
Masama kati	S07	100.7	Modern	Modern	Modern
Machare	S09	103.6	Modern	Modern	Modern
Baraa	S10	87.4	1100	Modern	Modern
Njoro	S12	89.0	900	Modern	Modern
Ilkloriti	W08	61.4	4000	2700	300
Moivo II	W09	70.9	2800	1500	Modern
Sanawari P/S	W10	61.7	3900	2600	500
Lorovani bondeni	W11	61.9	3900	2600	100
Oltulelei	W12	82.5	1500	200	Modern
Lorovani No. 4	W16	68.5	3000	1800	Modern
Mianzini	W17	66.6	3200	2000	Modern
Ilboru sec	W19	49.5	5700	4500	1400
Moilo	W21	79.0	1900	600	Modern
Missiori	W23	92.6	600	Modern	Modern
Mnadani No. 3	W25	89.7	900	Modern	Modern
Magereza	W26	64.2	3600	2300	Modern
Banana No. 5	W33	107.0	Modern	Modern	Modern

SID= Sample ID

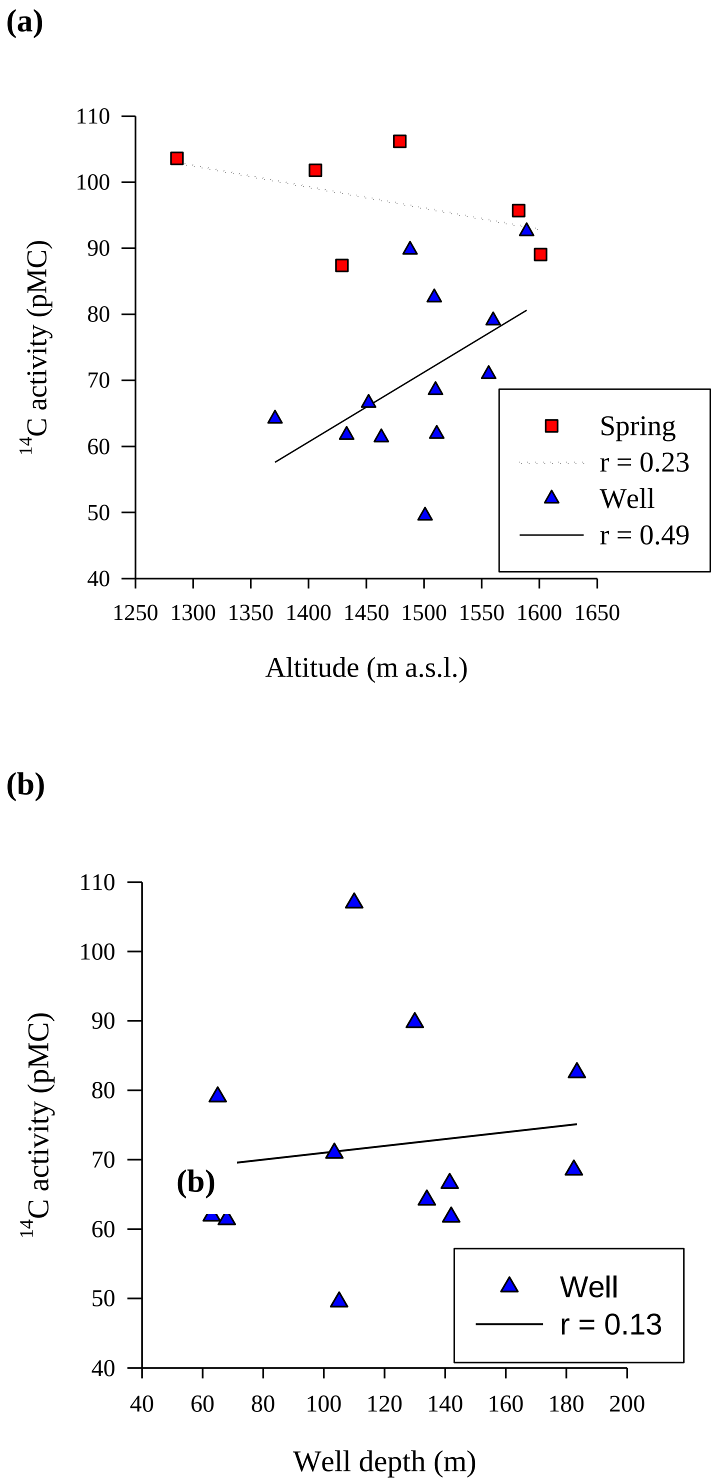


Figure 42: Scatter plot for ^{14}C activity associated with (a) altitude and (b) well depth

5.4 Discussion

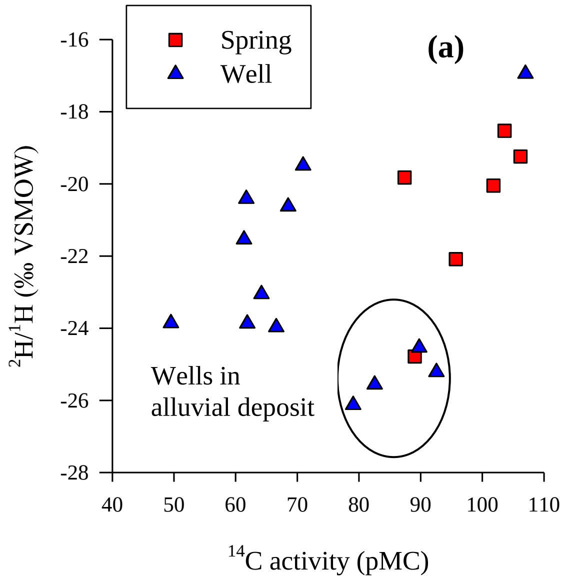
5.4.1 Moisture source

The stable isotope results gave a regression line with a slope of 6.7 which is close to but less than the one established by Rozanski *et al*. 1993 for the GMWL, i.e., 8.13 (Fig. 40) (Clark & Fritz, 1997) and the East African LMWL for Tanzania and Uganda with slope values of 7.01 and 7.38 respectively. Such a value indicates minimum or limited evaporation of infiltrated rain water during the recharge period in the study area. These findings are also supported by high deuterium excess values recorded by most groundwater samples ranging from 13 to 18‰ VSMOW (Table 19). Similar results were reported in a study conducted by Ghiglieri *et al*. (2012) at the North Eastern part of Mt. Meru where the values of deuterium excess varied from 10 to 17‰ VSMOW. Generally, at global scale the deuterium excess values range from -2 to about 10–15‰ VSMOW (Froehlich *et al*., 2001) depending on weather conditions. Moreover, other work reported in the literature shows that warm and dry conditions enhance evaporation, which leads to low or even negative deuterium excess values (Katsuyama *et al*., 2011; Steen-Larsen *et al*., 2014; Katsuyama *et al*., 2015). High deuterium values observed in the current study indicate dominance at low temperature and low humidity during groundwater recharge (Plummer *et al*., 2012).

5.4.2 Groundwater recharge

High ^{14}C activities observed in spring water (98.1±7.9 pMC) correspond with recently recharged groundwater in the study area (Fig. 43). The results indicate that the shallow aquifer is actively recharged and responds to seasonal variations. This is supported by spring flows (Fig. 44) whereby high flows are experienced during or immediate after the rainy season and vice versa during dry conditions. The spatial distribution of ^{14}C activities shows weak correlation (r = 0.49) with altitude (Fig. 42). The weak correlation may be due to groundwater mixing from different layers probably recharged at different times. High ^{14}C activity values were observed from wells located at high altitudes, the area which receives more rainfall compared to low altitudes in the southern slopes of Mt. Meru. This suggests that groundwater recharge is actively taking place in areas of high altitude on the slopes of the Mountain. However, no clear trends were established between ^{14}C activity and well depth (Fig. 42) probably indicating that most deep wells are tapping water from the same aquifer but at different depth. Additionally, spring waters are relatively more enriched with respect to hydrogen and oxygen isotopes (Table 19). This implies a higher fractionation effect due to evaporation in shallow groundwater than in deep wells. However, the difference in stable isotopic signatures is somehow narrow which implies that the recharge of both shallow and deep groundwater took place under similar climatic conditions (Hoque & Burgess, 2012).

(a)



(b)

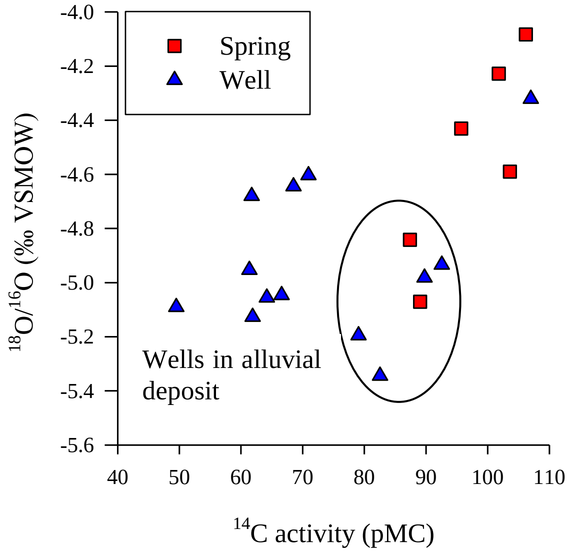


Figure 43: Relationship between stable isotopes and ^{14}C activity in water samples: (a) hydrogen, and (b) oxygen isotopes. The wells inside the *ellipse shape* are located in alluvial deposits.

Apart from ^{14}C dating, recent groundwater in springs was also evidenced by seasonal variations of spring-flow data established for two springs (S04 and S07) from 2014 to 2016 (Fig. 44). The flows respond positively during rainy season by increasing significantly and vice versa during dry months. This indicates that protection of these springs is of utmost importance otherwise the recharge cycle will be interfered by rapid urbanization and subsequently drying up or decrease of discharges. Nevertheless, the springs S10 and S12 recorded relatively lower values of ^{14}C activities, i.e., 87.4 and 89 pMC respectively. These activities probably indicate that the two springs originate from deep aquifers which don't respond easily to recharge from local precipitation.

Tritium results indicated low concentrations in all samples (<6.0 TU). However, the detection limit (6 TU) of the method used was not able to delineate exactly the amount in each sample which is expected to be low. In a similar study conducted on the northeastern Mt. Meru slope (Ghiglieri *et al.*, 2012), the maximum and mean values of 2.6 and 1.42 TU respectively were recorded in groundwater samples. The study also indicated tritium content of 2.8 TU in a rainwater sample. The low tritium content from both the previous and current studies suggest that groundwater in the study area is recently recharged.

5.4.3 Groundwater exploitation

The estimated uncorrected groundwater ^{14}C ages for investigated wells ranged from 5700 to about 600 years BP. Based on the Pearson corrected ^{14}C ages (Table 20), only four wells (W08, W10, W11 and W19) revealed old groundwater (1400 to 100 years). In terms of geological time scale, the ages seem to be young. However, it is quite a long period of time for the case of continuous groundwater exploitation and its respective replenishment through vertical recharge from local precipitation. The rest of the sampled wells have modern groundwater which suggests that the aquifer is actively recharged. The persisting water-level decline (Table 16) is probably a result of over-pumping practice as the groundwater development is not adequately controlled in the study area. Nevertheless, groundwater ages have been measured and reported worldwide ranging from months to millions of years (Sturchio *et al.*, 2004). Examples include (Bretzler *et al.*, 2011) who reported groundwater radiocarbon age in the main Ethiopian rift systems ranging from 800 to 5000 years BP at 80 to 260 m depths. In southern-east Tanzania (Bakari *et al.*, 2012b) reported ^{14}C age of groundwater was found to be ranging from 13 000 years BP in deep confined aquifers to 1300 years BP in shallow unconfined aquifers. Based on the current and previous studies, most groundwaters in the Rift valley systems were recharged in late Pleistocene and Holocene in the Quaternary period.

The age of groundwater is mainly affected by a number of factors including aquifer type and geology of the area (Wassenaar *et al.*, 1991; Sukhija *et al.*, 1996; Bretzler *et al.*, 2011). In the current study young and modern groundwater (high ^{14}C activity values) were observed in wells located at high altitude on the slopes of Mt. Meru which is the potential recharge zone of the study area (Ong'or & Long-cang, 2007). Other wells observed to have young water are located in areas dominated by alluvial deposits in the northwest (Figs. 39 and 43). The oldest groundwater (1400 years BP) was observed in a well located at low altitude (W19) in the central part of the study area. This zone is mainly dominated by the basalts formation, ranging from slightly weathered to fresh rocks (Appendix 2). Some of these wells are tapping water from different geological layers because of well-screen positions (Appendix 2). The position of screens at different depths within a single well could mean that the samples collected represented mixed groundwater i.e., young and old waters together. The mixed groundwater components could only be identified by applying a combination of tracers suitable for dating young groundwater (less than 50 years) such as ^{3}H/^{3}He or ^{85}Kr (Mazor, 1993; Corcho Alvarado *et al.*, 2007; Sültenfuβ *et al.*, 2011). The use of ^{14}C tracer facilitated only identification of groundwater component with age greater than 100 years whereas other components below this limit were categorized under modern groundwater. Generally, all samples considered in this research represent groundwater recharged in late Holocene.

Decrease in water levels and subsequent decline in well yields in the research area have been reported (Ong'or & Long-cang, 2007). This is in line with estimated groundwater ages of up to 1400 years BP. Such a long period of time is required to replenish the continuously abstracted groundwater through production wells. Additionally, potential groundwater recharge due to local precipitation is expected to be reduced because most production wells are located within built-up residential areas and more development is still taking place, expanding towards potential recharge areas. The development is likely to be interfering with groundwater recharge rates, particularly the infiltration rate of precipitation (Rose & Peters, 2001; Han *et al.*, 2017; Zomlot *et al.*, 2017). Based on estimated ^{14}C ages, the aquifer storage depletion in the study area is a result of groundwater over-pumping. However, future investigation on other factors likely to affect recharge mechanisms need to be undertaken.

These may include effects due to climate variability, earth quakes and tectonic movement, as the region is also affected by these natural phenomena.

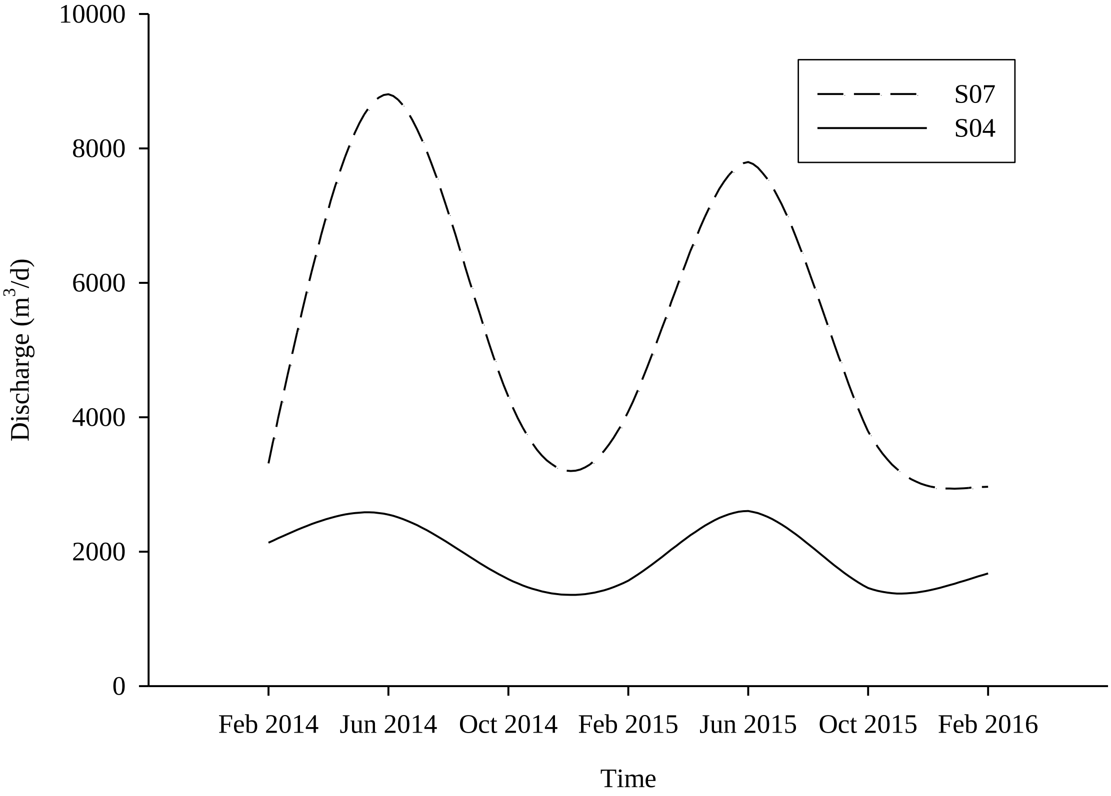


Figure 44: Seasonal variations of spring flows (S04 and S07) characterized by modern groundwater. Source: The data were compiled from daily flow measurements conducted by Arusha Urban Water Supply and Sanitation Authority. The flow is measured by means of a broad-crested weir with a rectangular control station.

5.5 Conclusions

The use of carbon-14 and stable isotope techniques for groundwater investigations has revealed abstraction of relatively old groundwater from Arusha aquifers. Groundwater ages estimated in the study area ranged from 1400 to 100 years BP. This long period of time is required to replenish the continuously abstracted groundwater through production wells. Generally, all groundwaters considered in this study were recharged in late Holocene. However, no clear trends were established between ^{14}C activity and well depth, probably indicating that most wells are tapping water from the same aquifer but at different depths or layers depending on screen positions. The oldest groundwater (1400 years BP) was observed in a well located at low altitude in the central part of the study area. This zone is mainly dominated by basalts formation, ranging from slightly weathered to fresh rocks. The carbon-14 results revealed young and modern groundwater in samples collected from shallow aquifers i.e., spring water and wells located in areas dominated by alluvial deposits at high altitudes. The presence of modern groundwater suggests that shallow aquifers are actively recharged and respond positively to seasonal variations. Additionally, spring flow data showed positive response during the rainy season by increasing flows significantly and vice versa during dry months. This indicates that water sources including recharge zones in the study area require a protection strategy to avoid drying up impact as well as decrease of discharge. Potential groundwater recharge due to local precipitation is expected to be reduced because most production wells and springs are located within built-up residential areas and more development is still taking place, expanding towards the recharge areas. The development is likely to be interfering with groundwater recharge mechanisms particularly the infiltration rate of precipitation. Due to continuous pumping of groundwater for public water supply in the study area and high mean residence times, as revealed by ^{14}C results, the existing groundwater abstraction rate in the study area will not sustain the future demand.

However, future investigation on other factors likely to affect recharge rates needs to be undertaken. These may include effects due climate variability, earth quakes and tectonic movement, as the region is also affected by these natural phenomena.

CHAPTER SIX

GENERAL DISCUSSION, CONCLUSION AND RECOMMENDATIONS

6.1 General discussion

Groundwater development particularly when there is no adequate control can result into adverse socioeconomic and ecological effects. The current global concern is groundwater depletion due to increasing demand driven by intensive irrigated agriculture and rapid population growth (Altchenko & Villholth, 2015; Amjath-Babu *et al.*, 2016). Some of the groundwater depletion effects include decreasing well yields, water level decline, rising pumping costs, water quality deterioration and damaging of aquatic ecosystem (Konikow & Kendy, 2005; Sishodia *et al.*, 2017). In order to ensure aquifer sustainability proper planning and management strategies should be developed and implemented. This needs adequate knowledge of the respective aquifers in terms of groundwater quality and quantity as well as recharge and discharge mechanisms. The quality of groundwater can be affected by either natural or anthropogenic influences. All these factors are equally important and their knowledge is vital in groundwater development and management. In many parts of Tanzania the major concern of groundwater quality has been salinity and fluoride levels to the extent of hindering various water sources from intended use. The findings of this study revealed among other issues groundwater depletion, elevated fluoride levels (naturally occurring), and abstraction of relatively old groundwater from Arusha wellfield.

Based on data from drilled boreholes and few published works, the level of groundwater salinity varies across the country (Chapter 2, Fig. 2). The main determining factors of the salinity occurrence and distributions include local geology, natural processes like tectonics and volcanism as well as anthropogenic activities such as intensive irrigated agriculture and fertilizer application. The coastal aquifers are characterized by brackish water (2271 to 5324 µS/cm) and saline groundwater in rare cases depending on the depth and distance of the well from the shoreline. This indicates that seawater has laterally intruded and mixed with fresh groundwater along the coastal region. Similar findings have been reported in previous works and identified Na-Cl and NaCa-HCO_3 as dominant water types (Mjemah, 2007; Bakari *et al.*, 2012a). However, confined deep coastal aquifers ranging from 200 to 600 m below ground surface are reported to have relatively low level of conductivity, chloride and nitrate (Bakari *et al.*, 2012b).

The northern part of Tanzania which is the focus of this study together with central Rift Valley were observed to have fresh groundwater but with relatively high salinity level (1000-2000 µS/cm). The region is dominated by volcanic rocks in the north and crystalline basement rocks in the central part which extends to Singida and Dodoma. Groundwater is hosted in fractured and weathered formations dominated by relatively high salinity levels (Nkotagu, 1996a; Bretzler *et al.*, 2011; Ghiglieri *et al.*, 2012) as a result of weathering and mineral dissolution during water-rock interaction. This is also evidenced by high Na^+ and low Ca^{2+} ions in groundwater encountered in the region (Bretzler *et al.*, 2011; Ghiglieri *et al.*, 2012) which implies long mean residence time. The levels of groundwater salinity in this region extend to some areas of Lake Victoria region (Fig. 2). In some areas, high salinity levels is reported to have been resulted from excessive irrigation water (Northey *et al.*, 2006; Batakanwa *et al.*, 2013) though the effect is limited in shallow aquifers. In volcanic region within the East African Rift System, trona dissolution is another factor which contribute to high salinity levels in groundwater due to evaporation and leaching processes (Kaseva, 2006; Pittalis, 2010). The rest of the country that is southern highlands, western and Lake Victoria regions which lay between great lakes have fresh groundwater with conductivity less than 1000 µS/cm. Similarly, groundwater with conductivity ranging from 200 to 1200 µS/cm has been encountered in central part of the country in particular Tabora region extending towards Lake Victoria (Davies & Dochartaigh, 2002). The origin of groundwater salinity in this region is due to dissolution of minerals from crystalline basement rocks which include granites, gneisses, quartzite, and migmatites (Davies & Dochartaigh, 2002).

Fluoride concentration in the study area was generally high in both spring and well waters. About eighty two (82) percent of the analyzed groundwater samples indicated fluoride concentrations higher than WHO guidelines and Tanzanian drinking water standards (1.5 mg/l). The concentrations varied from one location to another indicating different mineralogy or geological formation which may have different dissolution rate in the aquifer matrix (Ghiglieri *et al.*, 2012). In addition, water-rock interaction influences the concentration and rate of fluoride release into groundwater system. Low fluoride concentration in fractured and highly permeable phonolite hosted aquifers has been reported against high fluoride concentration in water originating from basalt and lahars formation (Ghiglieri *et al.*, 2010). This suggests that variations of fluoride concentrations in groundwater are controlled by both aquifer mineralogy and mean residence time. The spatial distribution analysis revealed high fluoride concentration in northern and north-western parts of the study area compared to south. High fluoride concentration in this zone is probably due to dominance in basalt formation and other fluoride rich volcanic materials such as lahars and volcanic ash which are known to contain and release significant amount of fluoride into groundwater in the region (Ghiglieri *et al*., 2012).

The spatial analysis of hydrogeochemical characteristics of Arusha wellfield revealed Na-K-HCO_3 type of water. The chemical properties of groundwater are dominated by alkali elements (Na^+ and K^+) and weak acids (HCO_3^-). Sodium ion was generally dominant in all samples with Magnesium being the least cation in the study area ($Na^+ > Ca^{2+} > K^+ > Mg^{2+}$). Such chemical behaviour in groundwater is explained by cations exchange reactions between Na^+ and Ca^{2+} which occur as a result of water-rock interaction as water moves through different mineralogical composition (Cerling *et al*., 1989; Ghiglieri *et al*., 2012; Utom *et al*., 2013). High concentrations of dissolved ions such as Na^+ and Ca^{2+} were observed in deep wells compared to shallow ones and springs. This suggests that groundwater abstracted from deep aquifers has long mean residence time since the time of recharge. The hydrogeochemistry of the groundwater is also supported with radioisotope signatures. The results revealed high ^{14}C activities in spring water (98.1±7.9 pMC) corresponding with recently recharged groundwater in the study area (chapter 5). The results indicate that the shallow aquifer is actively recharged and responds to seasonal variations but deep aquifers have relatively old water with mean radiocarbon age of up to 1400 years BP. The older groundwater was observed in central part of the study area. The lithology of this area as observed from well logs (Appendix 3) is dominated by basalts formation, ranging from slightly weathered to fresh rocks. Recently recharged water was mostly encountered in alluvial deposit formations believed to be the potential recharge area (Ong'or & Long-cang, 2007). Another evidence of modern groundwater in the study area is tritium results which indicated low concentrations in all samples. In a similar study conducted on the northeastern Mt. Meru slope (Ghiglieri *et al.*, 2012), the maximum and mean values of 2.6 and 1.42 TU respectively were recorded in groundwater samples. The study also indicated tritium content of 2.8 TU in a rainwater sample. The low tritium content from both the previous and current studies suggest that groundwater in the study area is recently recharged. Nevertheless, groundwater ages have been measured and reported worldwide ranging from months to millions of years (Sturchio *et al.*, 2004). In southern-east Tanzania, Bakari *et al.* (2012b) reported relatively old ^{14}C age of groundwater ranging from 13 000 years BP in deep confined aquifers to 1300 years BP in unconfined aquifers.

There is indication of groundwater contamination from anthropogenic influence particularly in springs and shallow wells. This was evidenced by high nitrate levels exceeding the recommended WHO guidelines (10.0 mg/l). The groundwater contamination in Tanzania is contributed by on site sanitation practice such as use of pit latrine and septic tank system connected to soak away pit (Nkotagu, 1996b; Mato & Kaseva, 1999; Kaown *et al.*, 2009; Elisante & Muzuka, 2015). However, very low concentrations of nitrate, chloride and sulphate (Chapter 3) were observed in groundwater samples collected from deep wells located in northern part of the study area. It was noted that shallow aquifers in the study area have been affected by anthropogenic pollution though measures need to be taken for both shallow and deep aquifers against such vulnerability.

A decrease in well discharge ranging from 10 to 57% for a period not exceeding 17 years has been observed in different wells within the wellfield in the study area. The decrease in well discharge is also accompanied by increasing drawdown of more than 1.0 m per year which indicates a serious groundwater depletion problem in the study area. Similar impact has been reported in central Tanzania (Taylor *et al*., 2013) and other many parts of the world which exceeds 1.0 m per year in extreme development conditions such as China, Spain and United States of America (Werner *et al*., 2013; Famiglietti, 2014; Huang *et al*., 2015; Custodio *et al.*, 2016; Kong *et al*., 2016). In this study, wells located in areas with less groundwater development such as Lorovani and Ilboru (chapter 4, Figs. 21 and 26) indicated slightly decrease in discharge compared to areas with intense groundwater development (Fig. 31). Groundwater development effects have been reported in many parts of the world particularly those with intense development. These impacts include land subsidence, deterioration of groundwater dependent-ecosystem which include drying up of springs, wetlands and decrease in volume of surface water bodies (Liu *et al*., 2011). Apart from groundwater depletion effect, quality deterioration especially increasing fluoride concentrations in groundwater has been reported. According to AUWSA personal communication (2015), one borehole at Ilboru Secondary school was abandoned due to increase in fluoride level after pumping for a couple of years. Therefore, an innovative approach is needed to rectify the ongoing unregulated groundwater development in the Arusha wellfield. The legal and institution framework responsible for water resources management are well structured. But the enforcement is still a challenge partly due to inadequate human and financial resources (Kabote & John, 2017). It was further revealed that lack of reliable hydrogeological information including interaction between surface water and groundwater hinders water resources management efforts particularly issuance of water use permit.

6.2 Conclusion

Geological and hydrogeochemical data, groundwater hydrographs, radioisotopes and environmental stable isotopes techniques were use to assess the groundwater abstraction trends and hydrogeochemical characteristics of Arusha wellfield in Arusha city. Groundwater salinity in terms of conductivity (EC) was also used to delineate salinity occurrence and distribution in different parts of Tanzania including Arusha where this study was carried out. The hydrogeochemical investigation revealed Na-K-HCO_3 water type with dominance of Na^+, K^+ and HCO_3^- as major dissolved ions. The hydrogeochemical assessment results and distribution of groundwater major cations (Na^+ , Ca^{2+} , K^+ , Mg^{2+}) and anions (HCO_3^- , Cl^- , SO_4^{2-} , F^-) in the study area indicate that groundwater chemistry is mainly influenced by aquifer lithology than anthropogenic activities.

With exception of fluoride and faecal contamination (not covered in this work) the quality of groundwater is generally suitable for drinking purpose and other socio-economic uses. About eighty two (82) percent of the analyzed groundwater samples indicated fluoride concentrations higher than WHO guidelines and Tanzanian drinking water standards (1.5 mg/l).

Groundwater hydrographs revealed groundwater depletion in the wellfield with a water level decline of about 1.0 m per year. The decline is accompanied by reduction in well discharges of about 10 to 57% observed from existing production wells for the past 17 years. The decline in water levels and subsequent reduction in discharges is a result of over-abstraction which is partly due to unregulated groundwater development in the area. More than 90% of individual wells were drilled without groundwater permit from water resources management authority. Therefore, even the amount of groundwater abstracted is not well known which makes a great challenge and difficult in water resources management. It is also anticipated that water level decline and subsequent reduction in well discharge will escalate the pumping costs due to increased distance from the dynamic water level to the ground surface.

The use of ^{14}C and stable isotope techniques for groundwater investigations revealed abstraction of relatively old groundwater from Arusha wellfield. Groundwater ages estimated in the study area ranged from 1400 years BP to modern groundwater. Such a long period of time is required to replenish the continuously abstracted groundwater through production wells. However, high ^{14}C activities in spring water (98.1±7.9 pMC) signify recently recharged groundwater in the study area. The presence of modern groundwater indicates that shallow aquifers are actively recharged and respond positively to seasonal variations.

Groundwater salinity mapping revealed both brackish and freshwater in different parts of the country. The brackish water is commonly found in coastal areas from Tanga in the north to Lindi in southeast. The salinity levels of coastal groundwater in terms of average conductivity ranged from 2271 to 5324 µS/cm. The elevated salinity level is mainly contributed by seawater intrusion. However, it varies depending on the depth and distance of the well from the shoreline. Confined deep coastal aquifers ranging from 100 to 600 m below ground surface have been reported to have relatively low levels of conductivity, chloride and nitrate. This suggests that the effect of seawater intrusion is more pronounced in unconfined shallow aquifers which have undergone intensive groundwater development in most coastal areas of Tanzania.

The northern and central Rift Valley region including Arusha was observed to have fresh groundwater but with relatively high salinity level (1000-2000 µS/cm). The region falls within the East African Rift System (EARS) which is dominated by volcanic and sedimentary rocks. The high salinity levels are partly due to dissolution of trona (evaporate mineral) which is commonly found in an EARS. The west part of the country including southern highlands and Lake Victoria region observed to have fresh groundwater with salinity levels less than 1000 µS/cm. The salinity level is relatively low and mainly influenced by local geology and in some rare cases may be contributed by anthropogenic activities such as irrigation water, fertilizer application and sewage effluents.

6.3 Recommendations

From the findings of this study, the following recommendations are put forward:

(i) The difference in fluoride concentration between spring and well waters is quite significant and can be explained by geology of the area. This calls up on a detailed geological study to precisely inform the entire spectrum of fluoride distribution and its origin in the study area

(ii) It is recommended to carry out groundwater flow patterns modelling to show how unregulated drilling affects the deep wells currently facing significant water level decline and subsequently discharge reduction.

(iii) Pumping test is required in Arusha wellfield for the purpose of establishing the radius of influence which can be used to guide the distance limit between wells for optimal groundwater abstraction and proper management of the resource.

(iv) Groundwater balance of the wellfield could not be performed due to limited information such as spring flow measurements in the area. Therefore, measurement of spring and river flows including measurements of gain and loss of stream flow between gauging stations is needed. Upon generation of the aforementioned information, a comprehensive analysis and development of management strategy for Arusha wellfield can be achieved.

(v) Over-abstraction has been revealed as one of the factors contributing to groundwater depletion in the study area. Future investigation on other factors likely to affect recharge mechanism needs to be undertaken.

(vi) Arusha wellfield is already stressed and it requires immediate interventions to ensure adequate and reliable water supply for the City and its neighbourhoods. To meet the current water demand which is already facing significant water deficit, consideration of alternative water sources is inevitable. Among the possible alternatives could be searching of new wellfield and rainwater harvesting.

(vii) More efforts to enforce existing laws and regulations governing water resources management in the wellfield and at basin level are needed. This will aid in limiting new development in depleted or stressed areas. Nevertheless, stringent measure should be taken against individuals who unlawful conduct groundwater development.

(viii) Groundwater permit issuance: As proper planning and management of groundwater resource depends on accurate information on which to base regulatory and management decisions. The permit issuance should consider interconnection between groundwater and surface water in the wellfield. Otherwise pumping water from aquifers that are hydraulically connected with surface water may cause significant effects such as reduced flows or drying up and subsequently damage of associated ecosystems.

(ix) For the purpose of understanding the amount of groundwater abstracted from the wellfield at a given time all production wells should have water flow meters and boreholes which were unlawful drilled in the wellfield should be legalized and their respective geological and hydrogeological data documented for proper water resources management and environmental protection.

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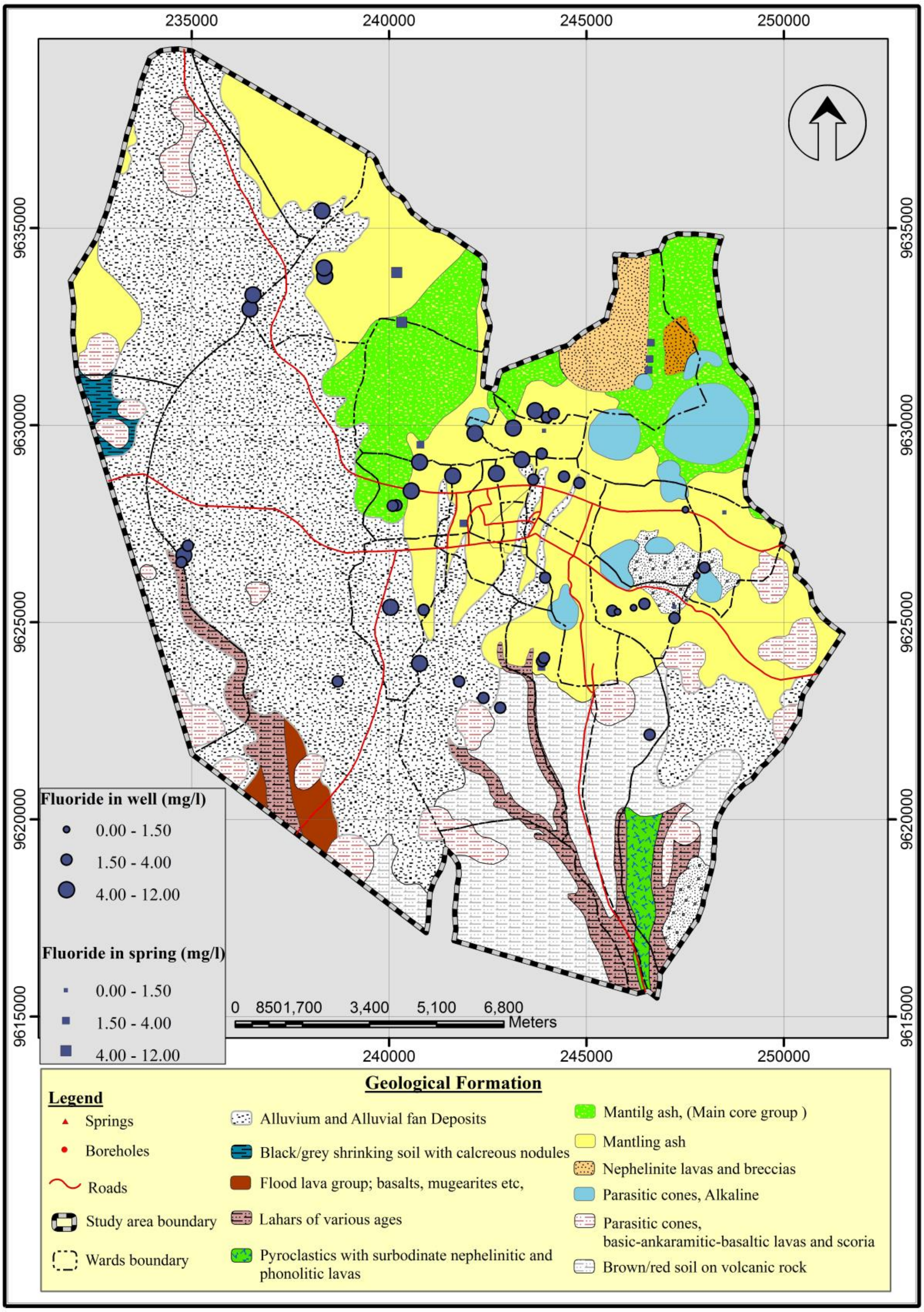
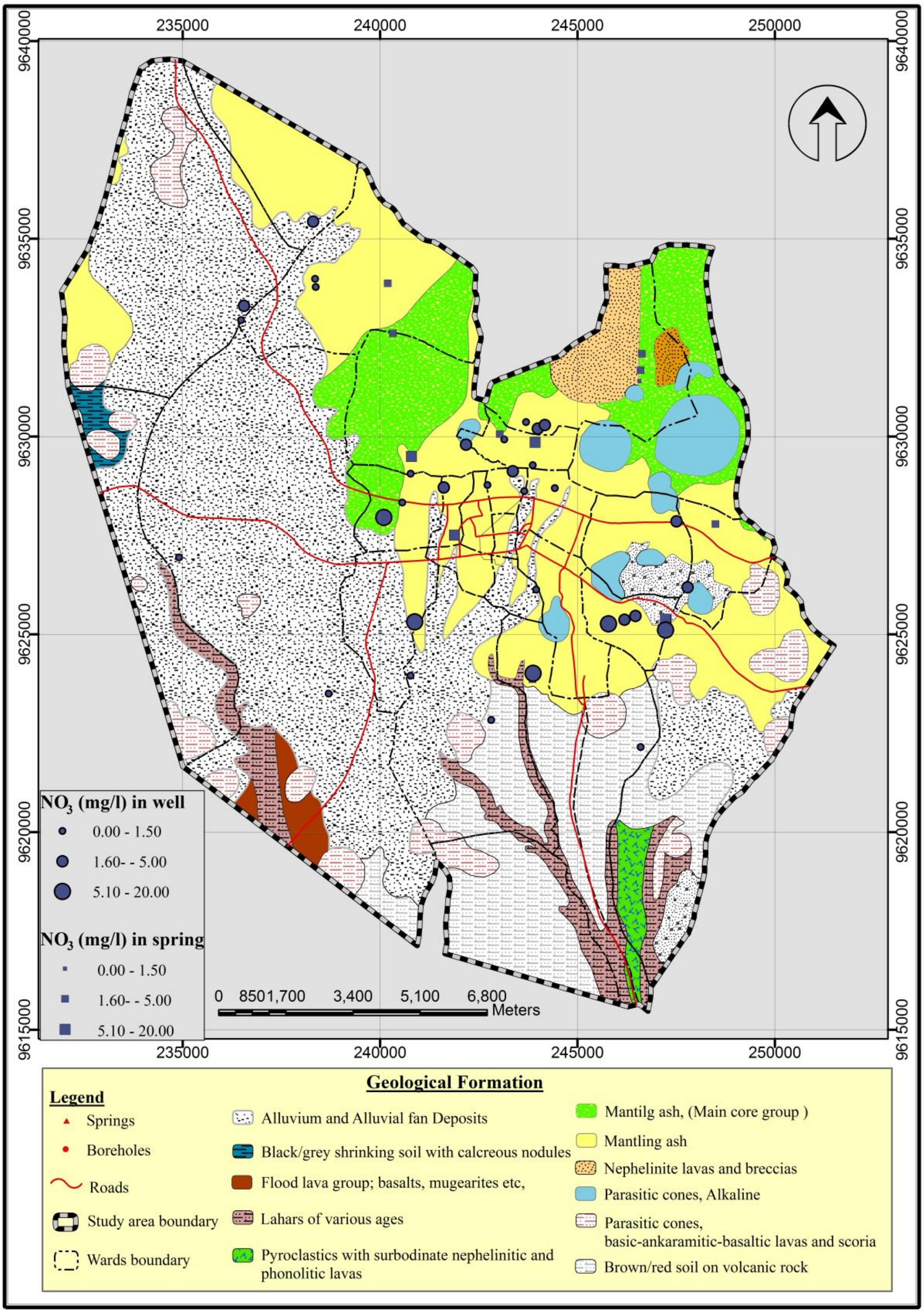
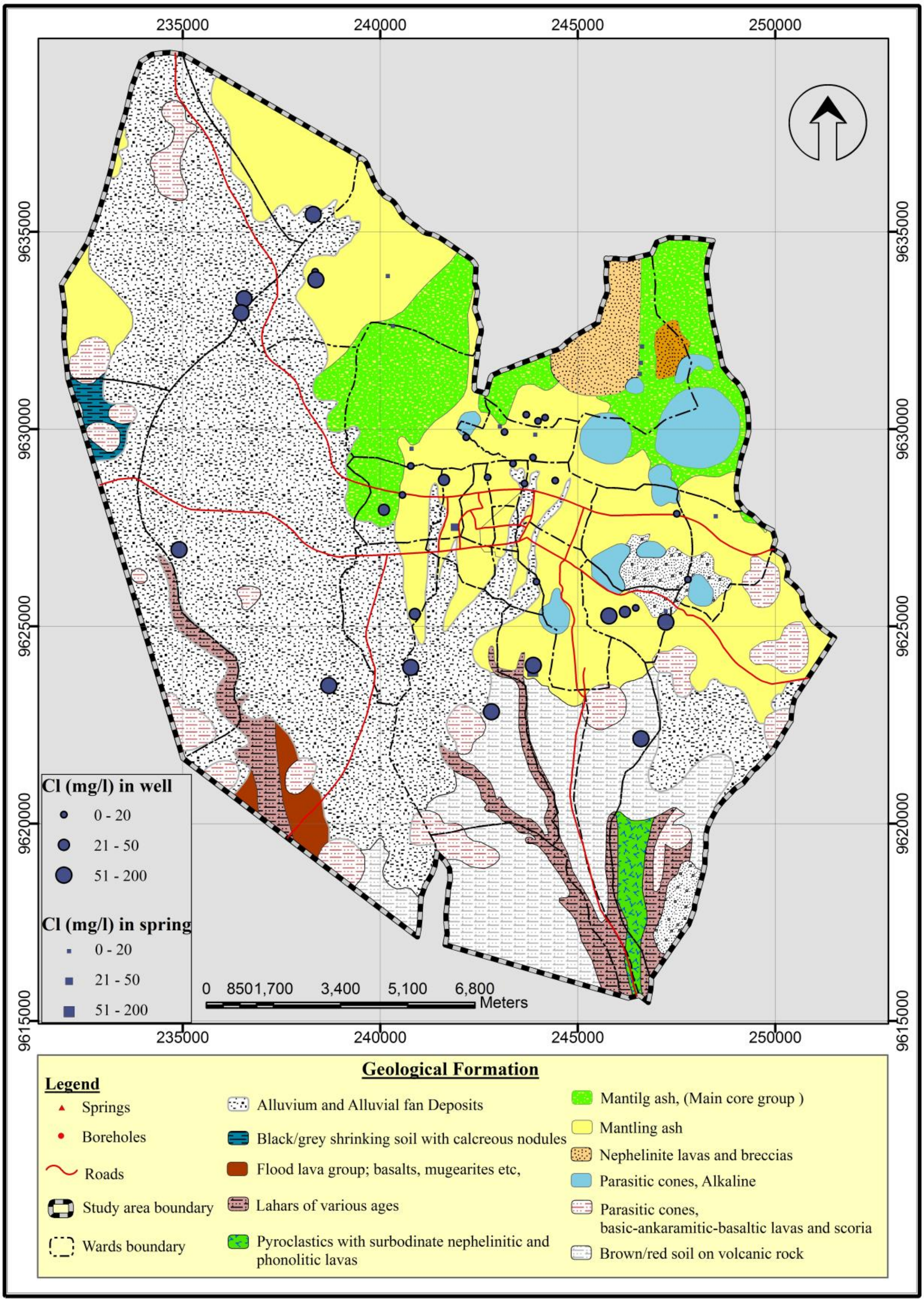
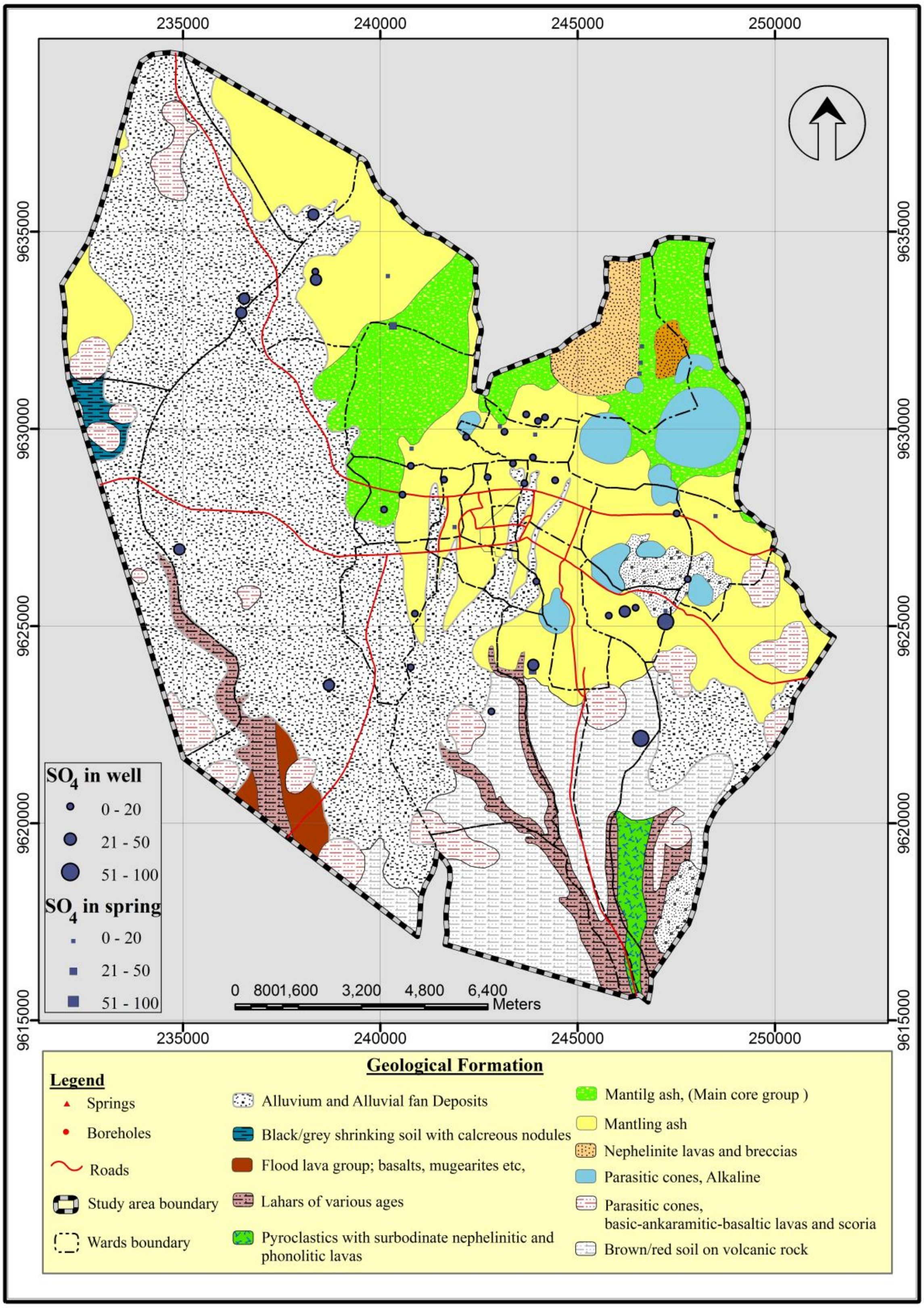
APPENDICES

Appendix 1: Groundwater quality spatial distribution

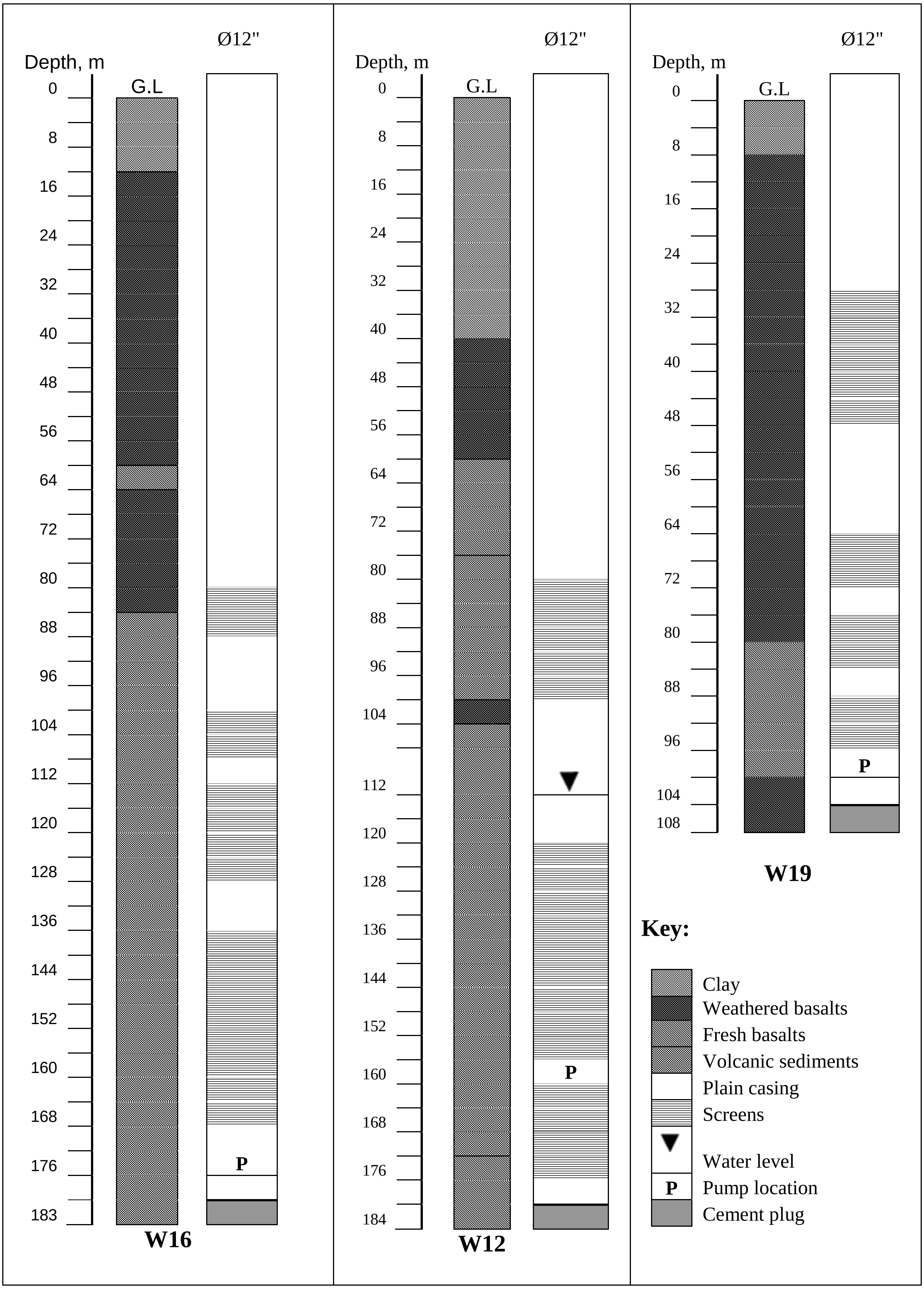


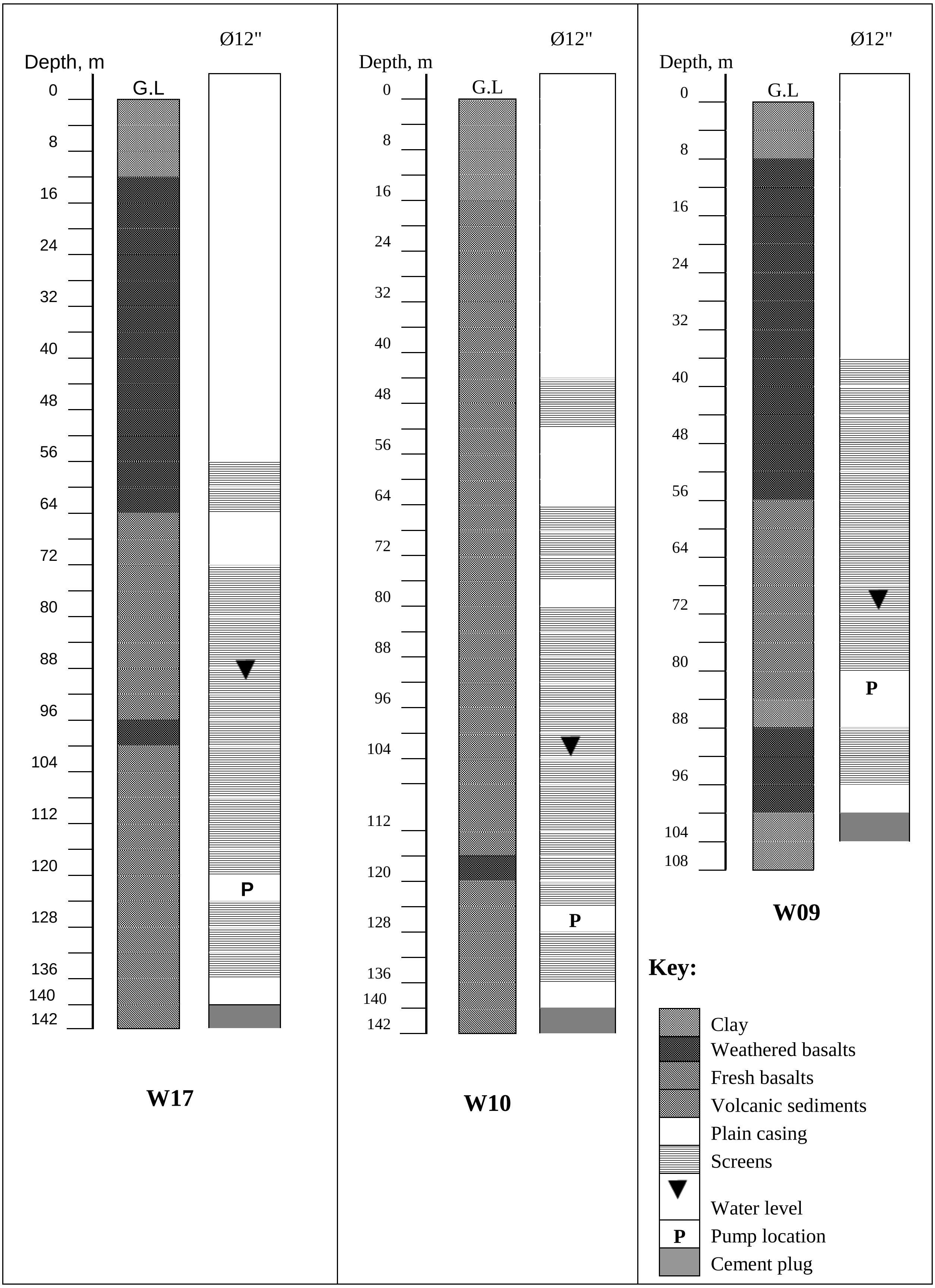

235000
240000
245000
250000
9640000
9635000
9630000
9625000
9620000
9615000
NO$_3$ (mg/l) in well
0.00 - 1.50
1.60- - 5.00
5.10 - 20.00
NO$_3$ (mg/l) in spring
0.00 - 1.50
1.60- - 5.00
5.10 - 20.00
0 8501,700 3,400 5,100 6,800
Meters
Geological Formation
Legend
Springs
Boreholes
Roads
Study area boundary
Wards boundary
Alluvium and Alluvial fan Deposits
Black/grey shrinking soil with calcreous nodules
Flood lava group; basalts, mugearites etc,
Lahars of various ages
Pyroclastics with surbodinate nephelinitic and phonolitic lavas
Mantilg ash, (Main core group)
Mantling ash
Nephelinite lavas and breccias
Parasitic cones, Alkaline
Parasitic cones, basic-ankaramitic-basaltic lavas and scoria
Brown/red soil on volcanic rock


235000
240000
245000
250000
9635000
9630000
9625000
9620000
9615000
Cl (mg/l) in well
0 - 20
21 - 50
51 - 200
Cl (mg/l) in spring
0 - 20
21 - 50
51 - 200
0 8501,700 3,400 5,100 6,800
Meters
Geological Formation
Legend
Springs
Boreholes
Roads
Study area boundary
Wards boundary
Alluvium and Alluvial fan Deposits
Black/grey shrinking soil with calcreous nodules
Flood lava group; basalts, mugearites etc,
Lahars of various ages
Pyroclastics with surbodinate nephelinitic and phonolitic lavas
Mantilg ash, (Main core group)
Mantling ash
Nephelinite lavas and breccias
Parasitic cones, Alkaline
Parasitic cones, basic-ankaramitic-basaltic lavas and scoria
Brown/red soil on volcanic rock

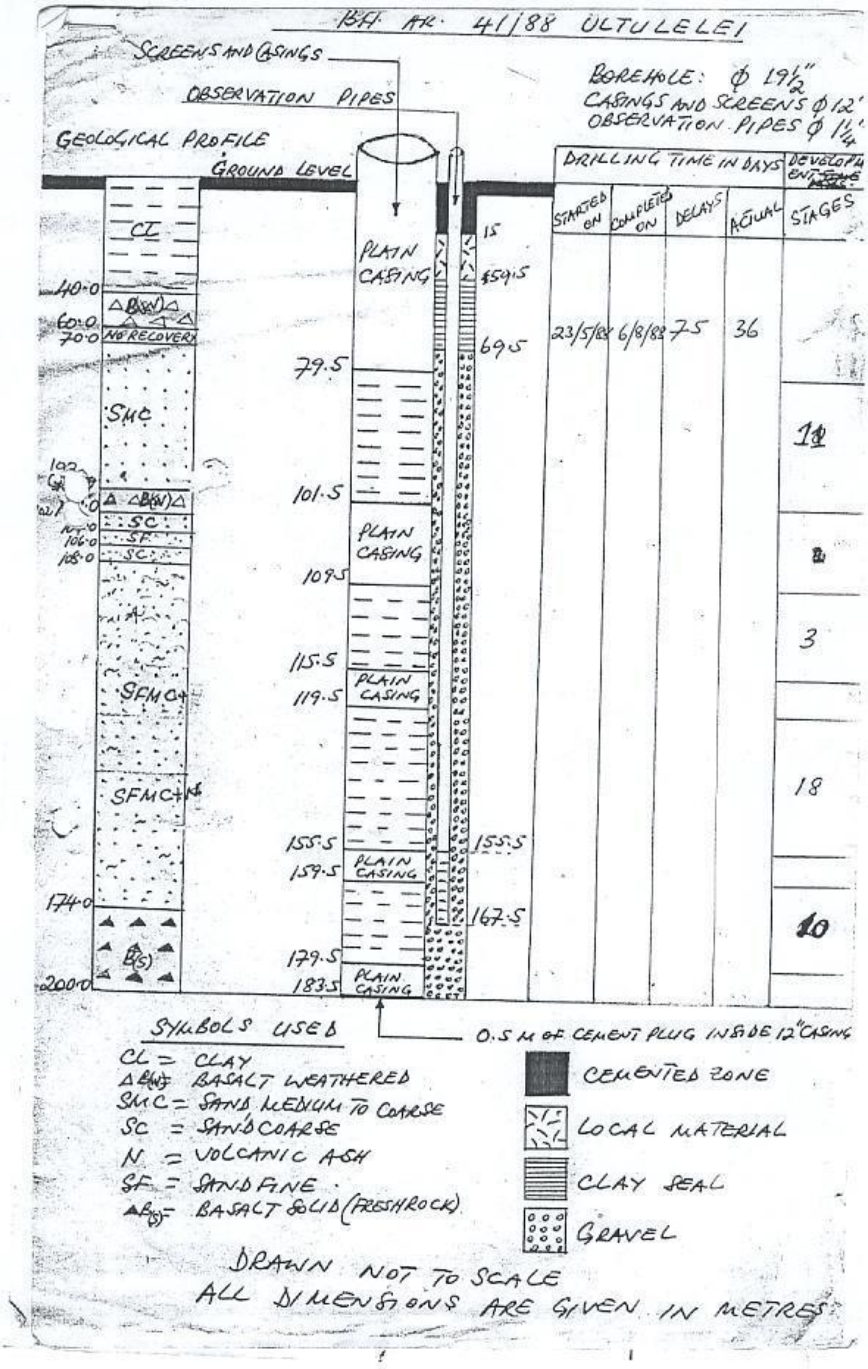

235000
240000
245000
250000
9635000
9630000
9625000
9620000
9615000
SO_4 in well
0 - 20
21 - 50
51 - 100
SO_4 in spring
0 - 20
21 - 50
51 - 100
0 8001,600 3,200 4,800 6,400
Meters
Geological Formation
Legend
Springs
Boreholes
Roads
Study area boundary
Wards boundary
Alluvium and Alluvial fan Deposits
Black/grey shrinking soil with calcreous nodules
Flood lava group; basalts, mugearites etc,
Lahars of various ages
Pyroclastics with surbodinate nephelinitic and phonolitic lavas
Mantilg ash, (Main core group)
Mantling ash
Nephelinite lavas and breccias
Parasitic cones, Alkaline
Parasitic cones, basic-ankaramitic-basaltic lavas and scoria
Brown/red soil on volcanic rock

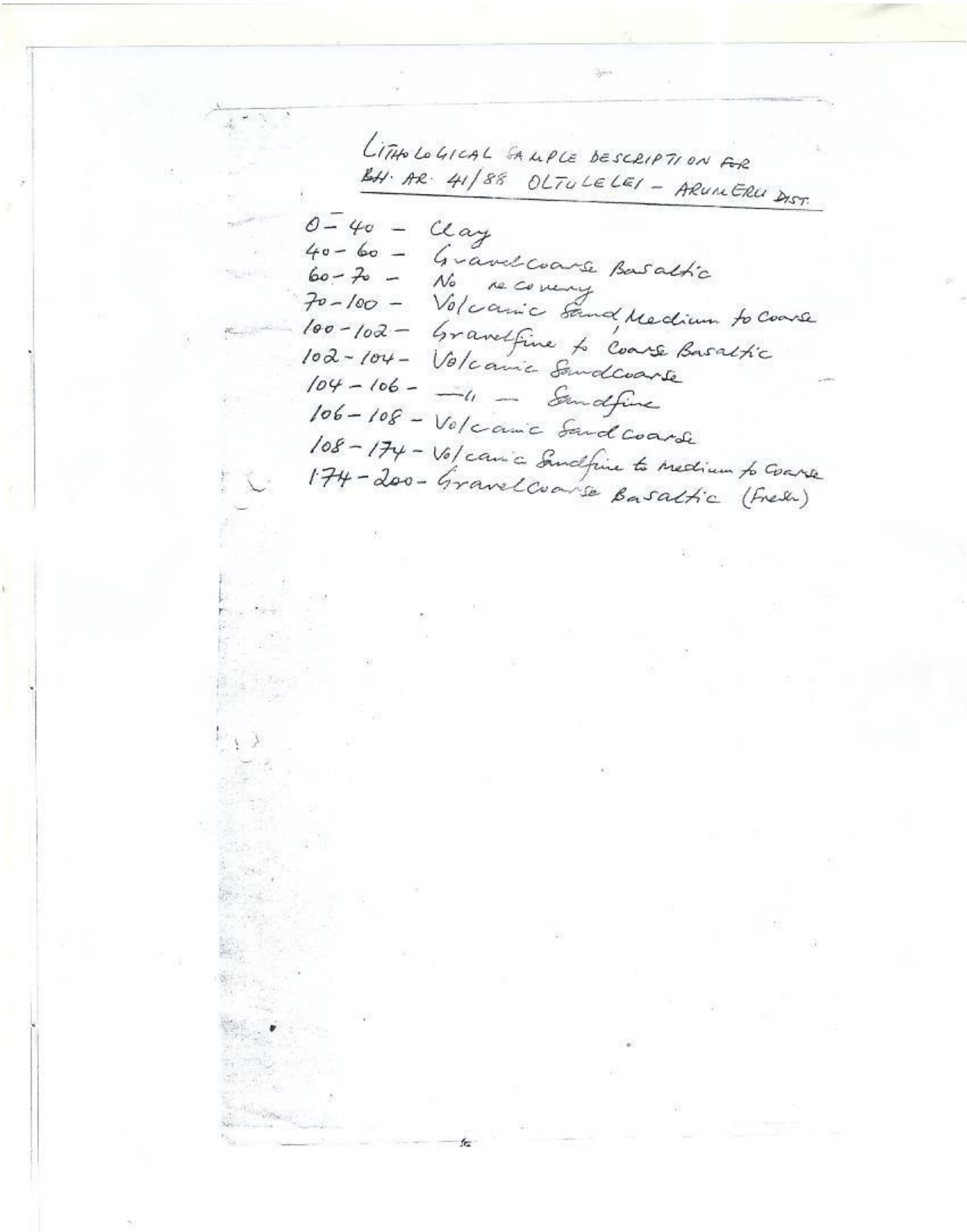
Appendix 2: Well lithology logs and completion details




Depth, m
G.L
Ø12"
0
8
16
24
32
40
48
56
64
72
80
88
96
104
112
120
128
136
140
142
P
W17
W10
W09
108
Key:
Clay
Weathered basalts
Fresh basalts
Volcanic sediments
Plain casing
Screens
Water level
P Pump location
Cement plug

Appendix 3: Well lithology logs

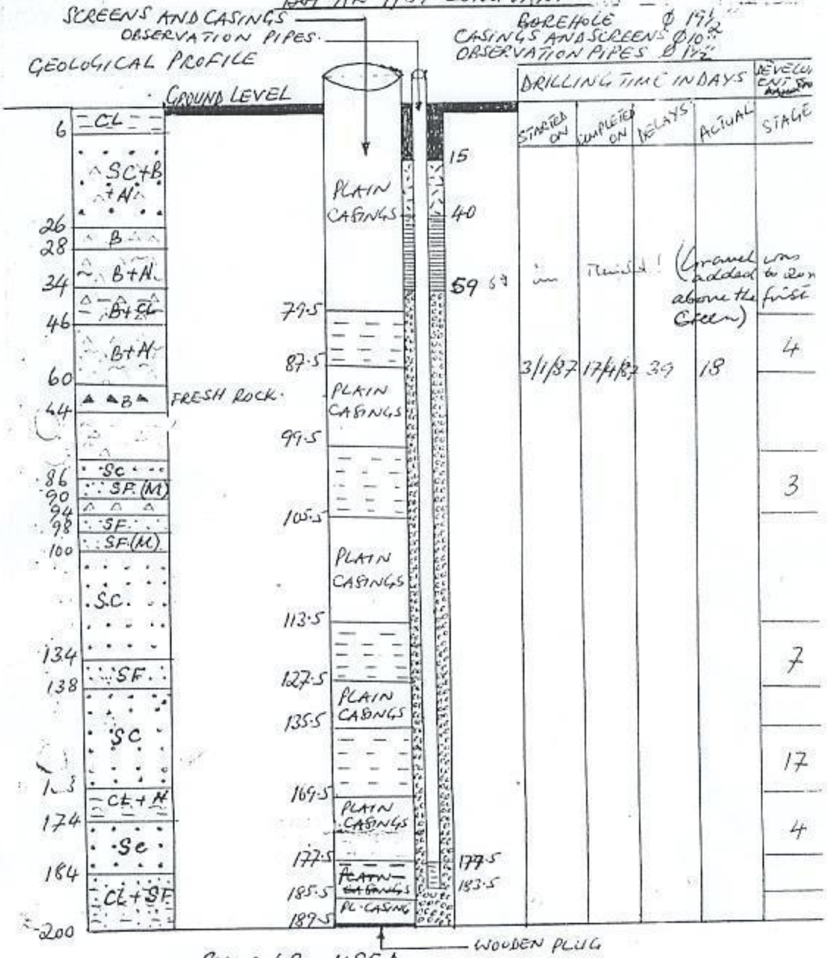




LITHOLOGICAL SAMPLE DESCRIPTION FOR
BH. AR. 41/88 OLTULELEI – ARUMERU DIST.

0 – 40 – Clay
40 – 60 – Gravelcoarse Basaltic
60 – 70 – No recovery
70 – 100 – Volcanic Sand, Medium to Coarse
100 – 102 – Gravelfine to Coarse Basaltic
102 – 104 – Volcanic Sandcoarse
104 – 106 – —"— Sandfine
106 – 108 – Volcanic Sandcoarse
108 – 174 – Volcanic Sandfine to medium to Coarse
174 – 200 – Gravelcoarse Basaltic (Fresh)

BH. AR. 1/87 LORUVANI

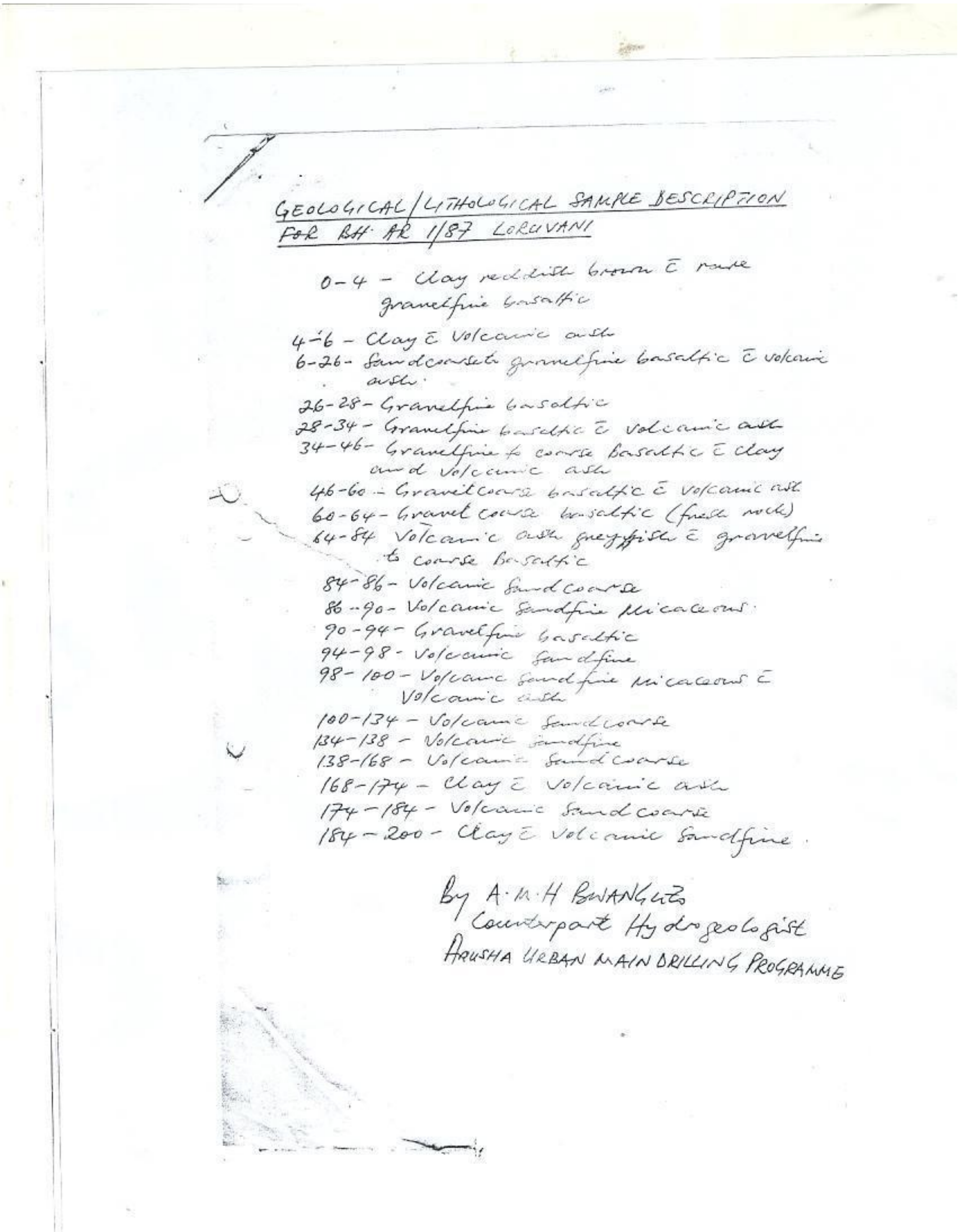


SYMBOLS USED

CL = CLAY
SC = SANDCOARSE
N = VOLCANIC ASH
ΔB = BASALT WEATHERED
SF(M) = SANDFINE MICACEOUS
SF = SANDFINE
▲B(S) = BASALT FRESHROCK

■ CEMENTED ZONE
▨ LOCAL MATERIAL
☰ CLAY SEAL
▦ GRAVEL.

DRAWN NOT TO SCALE.
ALL DIMENSIONS ARE GIVEN IN METRES

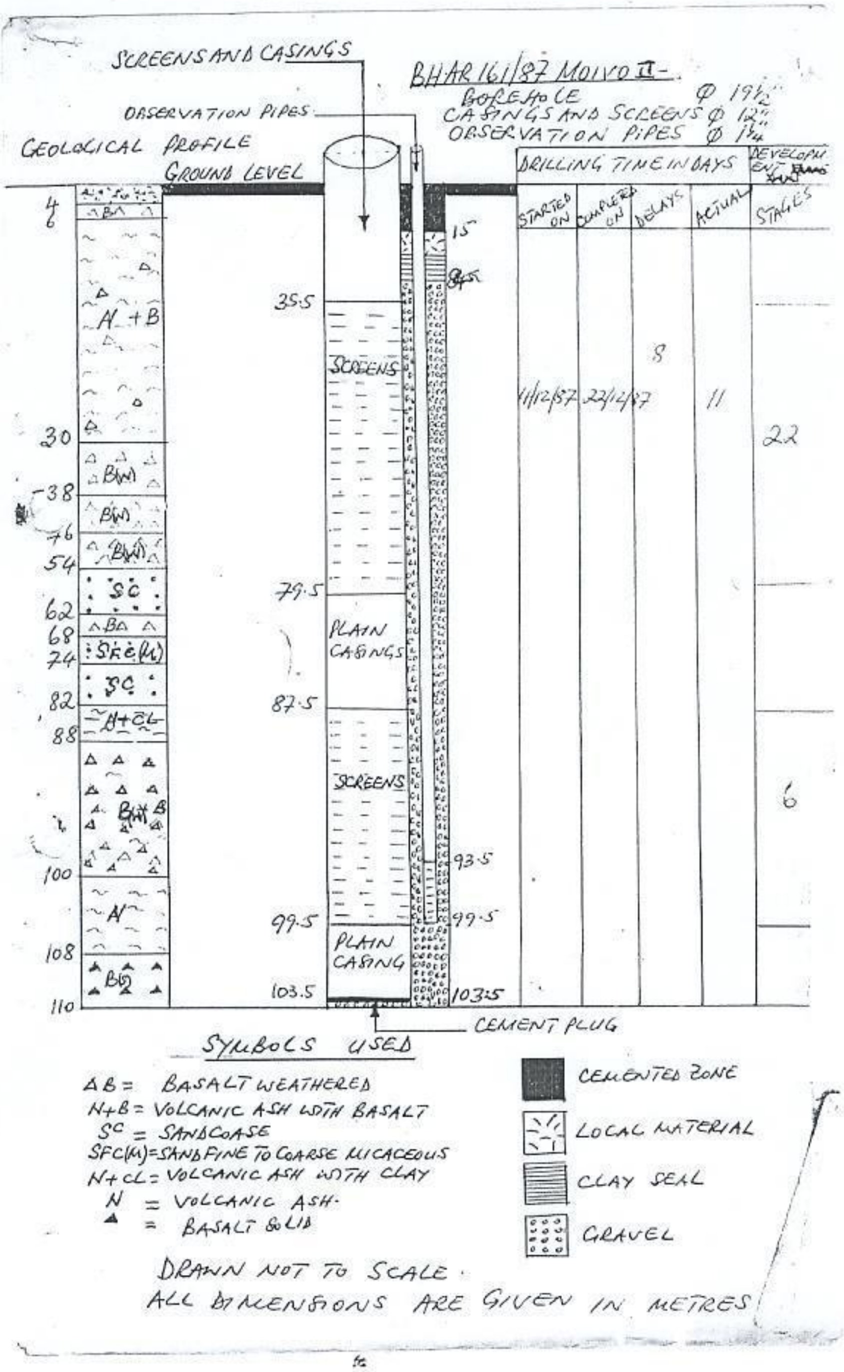


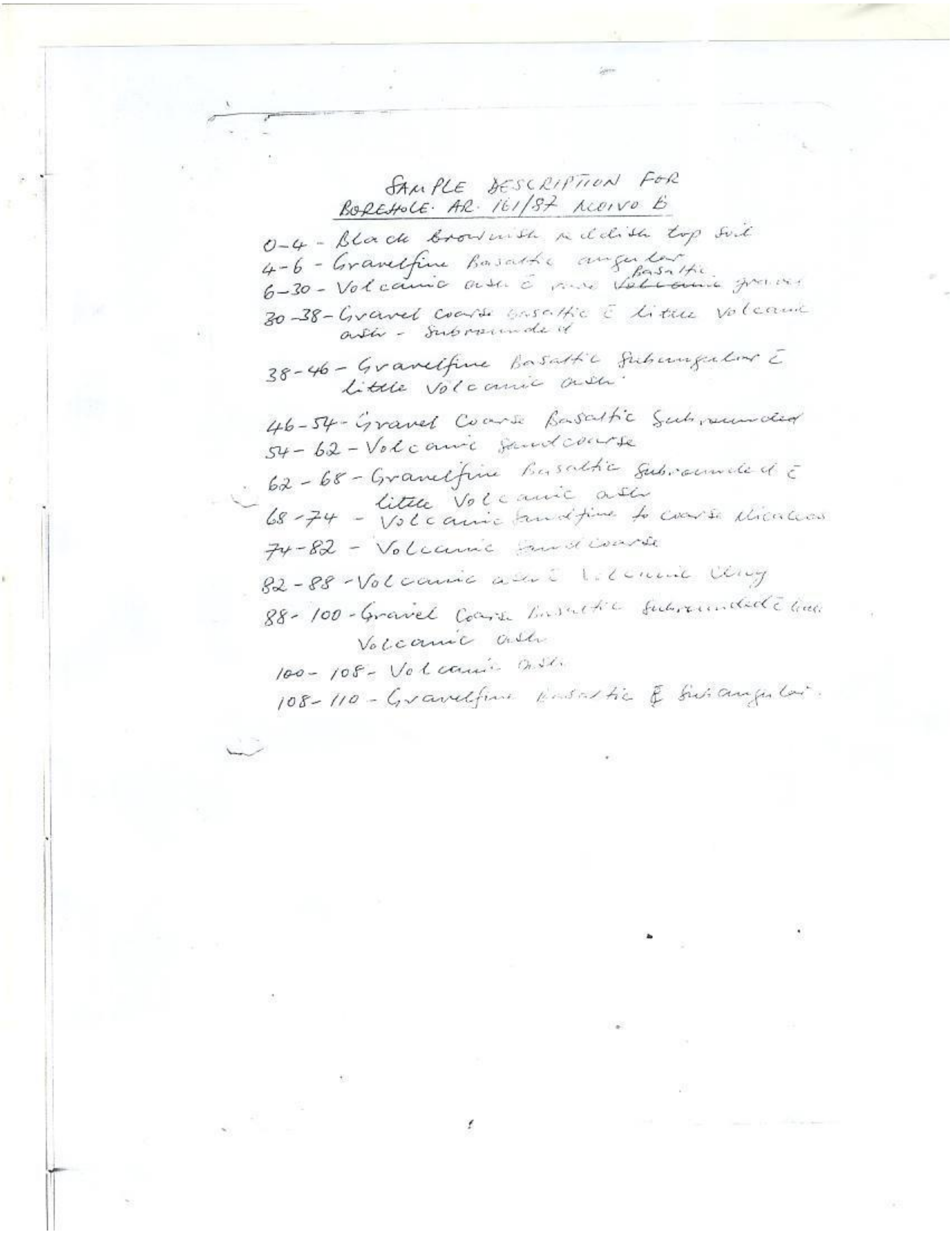
GEOLOGICAL/LITHOLOGICAL SAMPLE DESCRIPTION
FOR BH AR 1/87 LORUVANI

0-4 – Clay reddish brown c̄ rare gravelfine basaltic

4-6 – Clay c̄ Volcanic ash
6-26- Sandcoarse to gravelfine basaltic c̄ volcanic ash.
26-28- Gravelfine basaltic
28-34 - Gravelfine basaltic c̄ volcanic ash
34-46- Gravelfine to coarse basaltic c̄ clay and volcanic ash
46-60 – Gravelcoarse basaltic c̄ volcanic ash
60-64- Gravel coarse basaltic (fresh rock)
64-84 Volcanic ash greyyish c̄ gravelfine to coarse basaltic
84-86- Volcanic Sandcoarse
86-90- Volcanic Sandfine Micaceous.
90-94- Gravelfine basaltic
94-98- Volcanic Sandfine
98-100- Volcanic Sandfine Micaceous c̄ Volcanic ash
100-134 – Volcanic Sandcoarse
134-138 – Volcanic Sandfine
138-168 – Volcanic Sandcoarse
168-174 – Clay c̄ Volcanic ash
174-184 - Volcanic Sandcoarse
184-200 - Clay c̄ Volcanic Sandfine.

By A.M.H BWANGUZO
Counterpart Hydrogeologist
ARUSHA URBAN MAIN DRILLING PROGRAMME

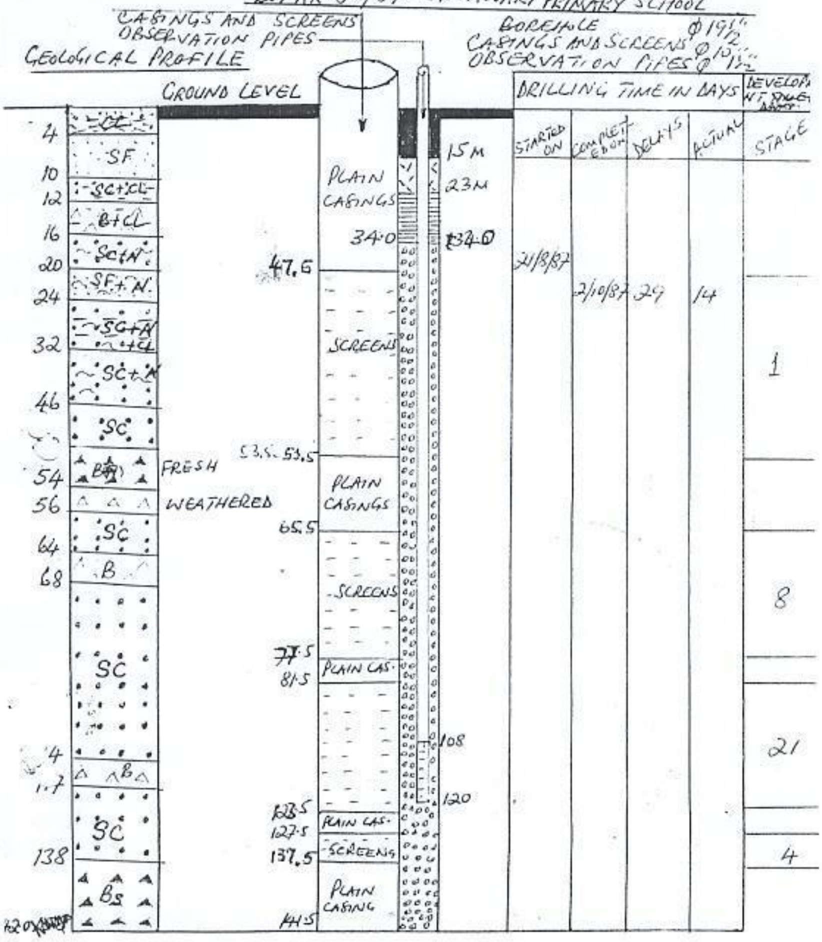

BHAR 161/87 MOIVO II-
BOREHOLE Φ 19½"
CASINGS AND SCREENS Φ 12"
OBSERVATION PIPES Φ 1¼"
SCREENS AND CASINGS
OBSERVATION PIPES
GEOLOGICAL PROFILE
GROUND LEVEL
DRILLING TIME IN DAYS
STARTED ON
COMPLETED ON
DELAYS
ACTUAL
DEVELOPMENT
STAGES
4
6
ΔBA
A+B
30
BW
38
BW
46
BW
54
SC
62
ΔBA
68
SFC(M)
74
SC
82
N+CL
88
BW+B
100
N
108
BS
110
15
35.5
SCREENS
79.5
PLAIN CASINGS
87.5
SCREENS
93.5
99.5
PLAIN CASING
103.5
103.5
1/12/87
22/12/87
8
11
22
6
CEMENT PLUG
SYMBOLS USED
ΔB = BASALT WEATHERED
N+B = VOLCANIC ASH WITH BASALT
SC = SANDCOASE
SFC(M) = SAND FINE TO COARSE MICACEOUS
N+CL = VOLCANIC ASH WITH CLAY
N = VOLCANIC ASH
▲ = BASALT SOLID
CEMENTED ZONE
LOCAL MATERIAL
CLAY SEAL
GRAVEL
DRAWN NOT TO SCALE.
ALL DIMENSIONS ARE GIVEN IN METRES



SAMPLE DESCRIPTION FOR
BOREHOLE· AR· 161/87 ACOIVO B

0-4 - Black brownish reddish top soil
4-6 - Gravelfine Basaltic angular
6-30 - Volcanic ash c̄ fine Basaltic ~~Volcanic~~ gravel
30-38 - Gravel coarse basaltic c̄ little volcanic ash - Subrounded
38-46 - Gravelfine Basaltic Subangular c̄ little Volcanic ash
46-54 - Gravel Coarse Basaltic Subrounded
54-62 - Volcanic Sandcoarse
62-68 - Gravelfine Basaltic Subrounded c̄ little Volcanic ash
68-74 - Volcanic Sandfine to coarse micaceous
74-82 - Volcanic Sand coarse
82-88 - Volcanic ash c̄ Volcanic clay
88-100 - Gravel Coarse Basaltic Subrounded c̄ little Volcanic ash
100-108 - Volcanic ash
108-110 - Gravelfine basaltic c̄ Subangular.

BH AR. 83/87 - SANAWARI PRIMARY SCHOOL



SYMBOLS USED

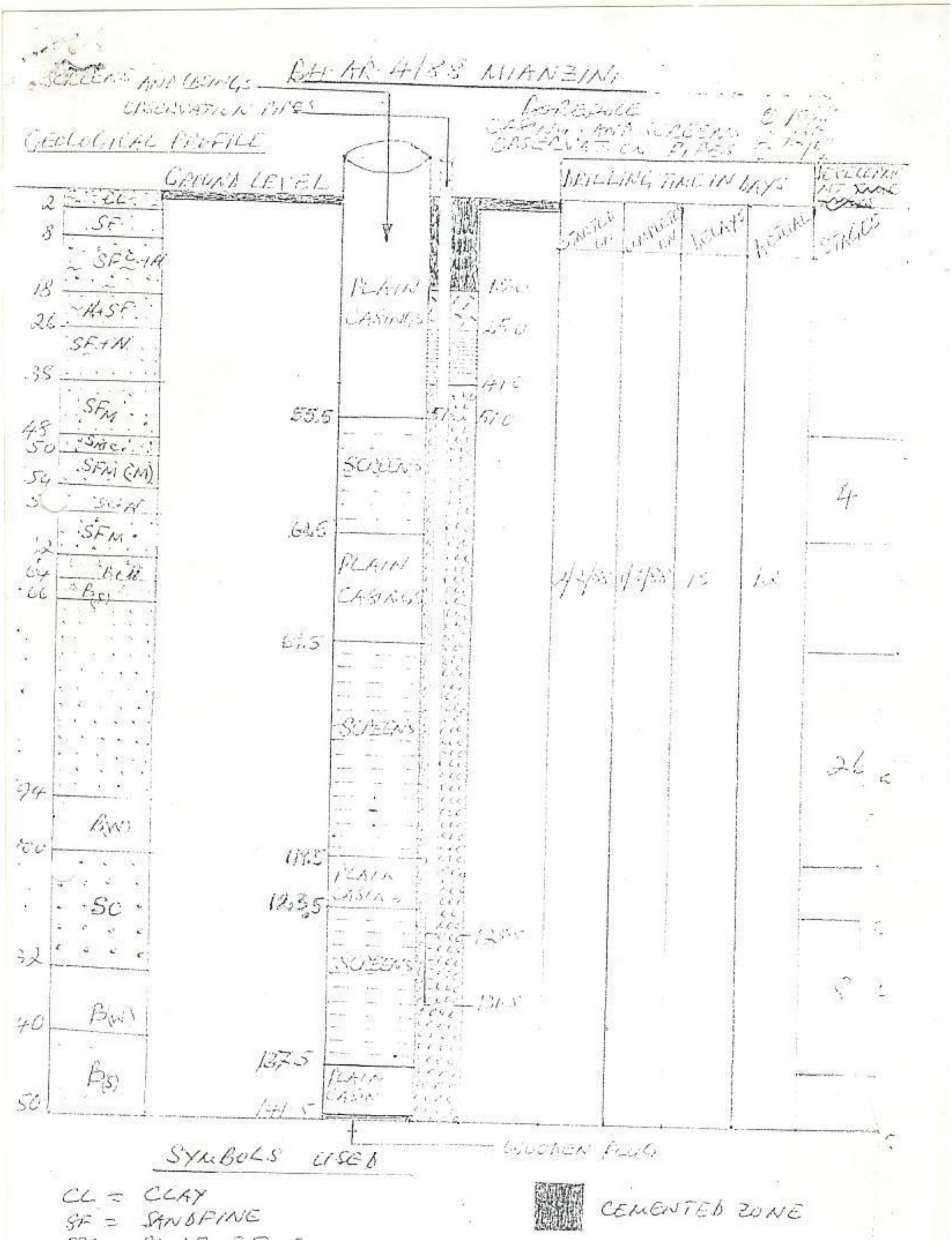
CL = CLAY
SF = SANDFINE
SC = SANDCOARSE
N = VOLCANIC ASH
△B = BASALT WEATHERED
▲B = BASALT (SOLID) FRESHROCK

■ CEMENTED ZONE
▨ LOCAL MATERIAL
☰ CLAY SEAL
⠿ GRAVEL

DRAWN NOT TO SCALE
ALL DIMENSIONS ARE GIVEN IN METRES

GEOLOGICAL/LITHOLOGICAL SAMPLE DESCRIPTION FOR BH AR 83/87 SANAWARI

0-4 – Top soil brownish
4-10 – Volcanic sand fine greyish
10-12 – Volcanic sand coarse c̄ clay
12-16 – Gravel fine to coarse basaltic weathered c̄ clay
16-20 – Volcanic sand coarse c̄ volcanic ash
20-24 – Volcanic sand fine c̄ volcanic ash
24-32 – Volcanic sand coarse c̄ clay c̄ volcanic ash
32-46 – Volcanic sand coarse c̄ volcanic ash
46-50 – Volcanic sand coarse dark-grey
50-54 – Gravel fine basaltic (Hard basalt)
54-56 – Gravel coarse basaltic (weathered)
56-64 – Volcanic sand coarse c̄ minor volcanic ash
64-68 – Gravel fine to coarse basaltic
68-114 – Volcanic sand coarse
114-117 – Gravel fine basaltic
117-138 – Volcanic sand coarse
138-158 – Gravel fine to coarse basaltic


BH AR 4/88 MIANZINI
SCREENS AND CASINGS
OBSERVATION PIPES
GEOLOGICAL PROFILE
GROUND LEVEL
BOREHOLE
CASING AND SCREENS
OBSERVATION PIPES
DRILLING TIME IN DAYS
STARTED ON
COMPLETED ON
TOTAL
ACTUAL
DEVELOPMENT
STAGES
2
CL
8
SF
SF+H
18
H+SF
26
SF+N
38
SFM
48
50
SMC
SFM (M)
54
SCH
SFM
64
BCH
66
B(S)
94
B(W)
100
SC
32
40
B(W)
B(S)
50
PLAIN CASINGS
55.5
SCREENS
61.5
PLAIN CASINGS
81.5
SCREENS
119.5
PLAIN CASING
123.5
SCREENS
137.5
PLAIN CASING
141.5
15.0
25.0
41.0
51.0
128.0
135.5
4/4/88
15
28
4
26
8
WOODEN PLUG
SYMBOLS USED
CL = CLAY
SF = SANDFINE
CEMENTED ZONE

GEOLOGICAL/LITHOLOGICAL SAMPLE DESCRIPTION FOR BH: NR: 4/88 MANZINI

0-2 - Brownish top soil
2-8 - Volcanic Sandfine
8-18 - Volcanic Sandfine to coarse c̄ Volcanic ash black brownish
18-26 - Volcanic ash c̄ Volcanic Sandfine greyyish in colour
26-38 - Volcanic Sandfine c̄ Volcanic ash greyyish in colour
38-48 - Volcanic Sandfine to medium
48-50 - Volcanic Sand medium to coarse greyyish brown
50-54 - Volcanic Sandfine to medium Micaceous grey brownish in colour.
54-56 - Volcanic ash c̄ Volcanic Sandcoarse
56-62 Volcanic Sandfine to medium black greyyish
62-64 - Gravelcoarse basaltic c̄ Volcanic ash
64-66 - Gravelcoarse basaltic black greyyish
66-94 - Volcanic Sand medium to coarse blackish in colour
94-100 - Gravelfine to coarse basaltic blackish in colour
100-132 - Volcanic Sandcoarse black-greyish in colour
132-144 - Gravelfine to medium basaltic black-greyyish
144-152 - Gravelfine to coarse basaltic Subangular

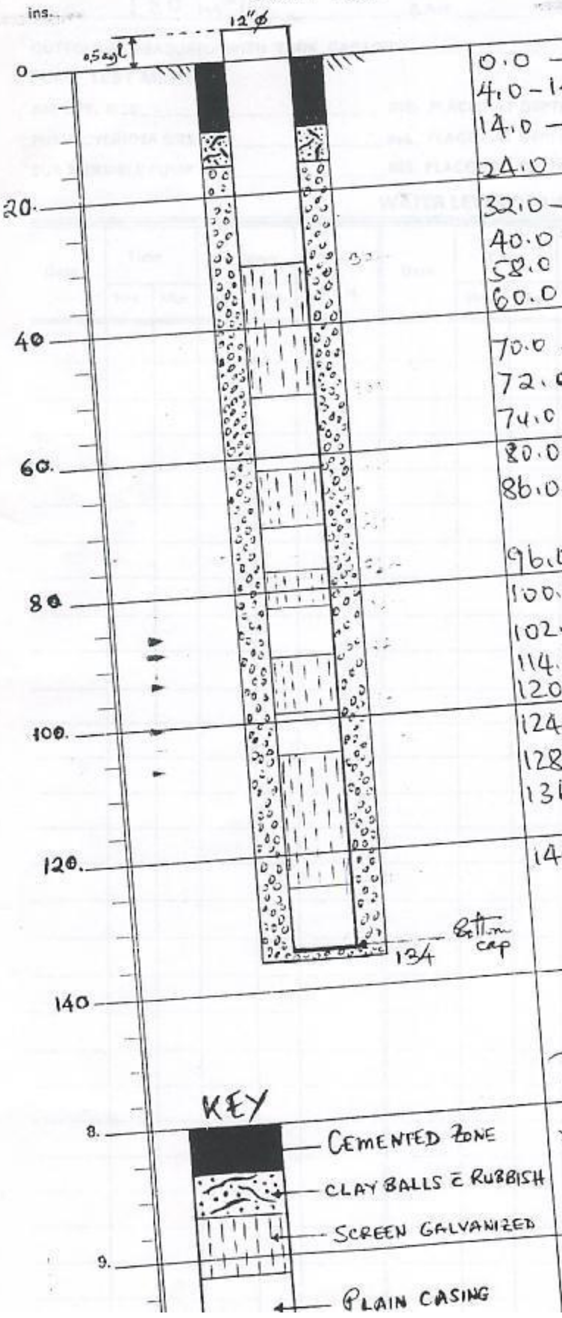
9. BHs. RECORD DRAWING AR |46|92

(TO BE COMPLETED BY I. (D). OR D/S.)

SCALE 1" TO ~~FT.~~ 20 M

10. BHs. GEOLOGICAL LOG

(TO BE COMPLETED BY GEOLOGIST)



0.0 – 4	Clay brown
4.0 – 14.0	Sand fine brown
14.0 – 24.0	Sand medium to coarse brown
24.0 – 32.0	Sand medium grey
32.0 – 40.0	Sand coarse brown
40.0 – 58.0	Sand fine grey
58.0 – 60.0	Sand coarse grey
60.0 – 70.0	Sand medium to coarse grey
70.0 – 72.0	Sand fine brown
72.0 – 74.0	Sand coarse grey
74.0 – 80.0	Sand fine to medium grey
80.0 – 86.0	Sand coarse grey
86.0 – 96.0	Sand medium to coarse grey
96.0 – 100.0	Sand fine to medium grey
100.0 – 102.0	Sand coarse grey
102.0 – 114.0	Sand fine to medium grey
114.0 – 120.0	Sand coarse brown
120.0 – 124.0	Sand fine grey
124.0 – 128.0	Sand coarse brown
128.0 – 136.0	Sand medium grey
136.0 – 140.0	Sand coarse angular to subangular grey
140.0 – 150.0	Sand fine to medium grey

Tech 1 (H/Geology)

The entire sandy profile is from volcanic rocks.

THE UNITED REPUBLIC OF TANZANIA

COMPLETION FORM

W.E. & M. From W.W. 10

BOREHOLE NO. AR / 46 / 92 DRILLED BY, RIG. NO. 37 & 47 SCHRAmm

LOCATION/ESTATE ILBORU SEC. SCHOOL AREA ARUMERU REGION ARUSHA

NAME OF APPLICANT ARUSHA URBAN WATER SUPPLY

DATE OF COMMENCEMENT DATE OF COMPLETION

1. STRATA:

FROM ·m·		TO ·m·		GENERAL DESCRIPTION
0	0	4	0	Clay brown
4	0	14	0	Sand fine brown
14	0	24	0	Sand medium to coarse brown
24	0	32	0	Sand medium grey
32	0	40	0	Sand coarse brown
40	0	58	0	Sand fine grey
58	0	60	0	Sand coarse
60	0	70	0	Sand fine to medium grey
70	0	72	0	Sand fine brown
72	0	74	0	Sand coarse grey
74	0	80	0	Sand fine to medium grey
80	0	86	0	Sand coarse grey
86	0	96	0	Sand medium to coarse grey
96	0	100	0	Sand fine to medium grey
100	0	102	0	Sand coarse grey
102	0	114	0	Sand fine to medium grey
114	0	120	0	Sand coarse brown
120	0	124	0	Sand fine grey
124	0	128	0	Sand coarse brown
128	0	136	0	Sand medium grey
136	0	140	0	Sand coarse angular to subangular grey
140	0	150	0	Sand fine to medium grey

2. WATER:

Struck at Depth ______ feet ______ inches

W.L. rose to ______ feet ______ inches B.G.L.

Yield tasted 180 m3/H G.P.H.

Water quality to taste Good

3. DIAMETER DRILLED AND DEPTH:

12¼ inch to 150 M ins.

______ inch to ______ ft. ______ ins

______ inch to ______ ft. ______ ins

Depth on Completion 150 M inches

4. CASING/SCREEN LEFT IN HOLE:

Type		Dia		Length	
	Casing		inch.	ft.	ins
	Casing		inch.	ft.	ins.
	Casing		inch.	ft.	ins.
	Screen		inch.	ft.	ins.
	Screen		inch.	ft	ins.
	Screen		inch.	ft.	ins.

Casing above G.L. 0.5 M. inch.

Top of Casing Secured WITH A CAP

Bottom end of Casing Protected with A CAP

5. FINISH OF SECTION UNCASED:

Hole Uncased — ft. ins

Back-Filled to ______ ft. ins.

Filled with ______ Average Size ______ ins

Other Method ______

6. GRAVEL SCREEN:

Gravel Type ______ Grav.

Average Size ______ ins

Inserted from ______ ft. ______ ins. to ______ ft. ______ ins.

No. cu. ft. inserted ______ Surged Hrs.

No. cu. ft. of Gravel inserted after Surging

7. DRILLING METHOD

Air-Rotary to ______ ft. ins

Mud-Rotary to ______ ft. ins

Air-Hammer to ______ ft. ins.

Rev-Circulation to ______ ft. ins.

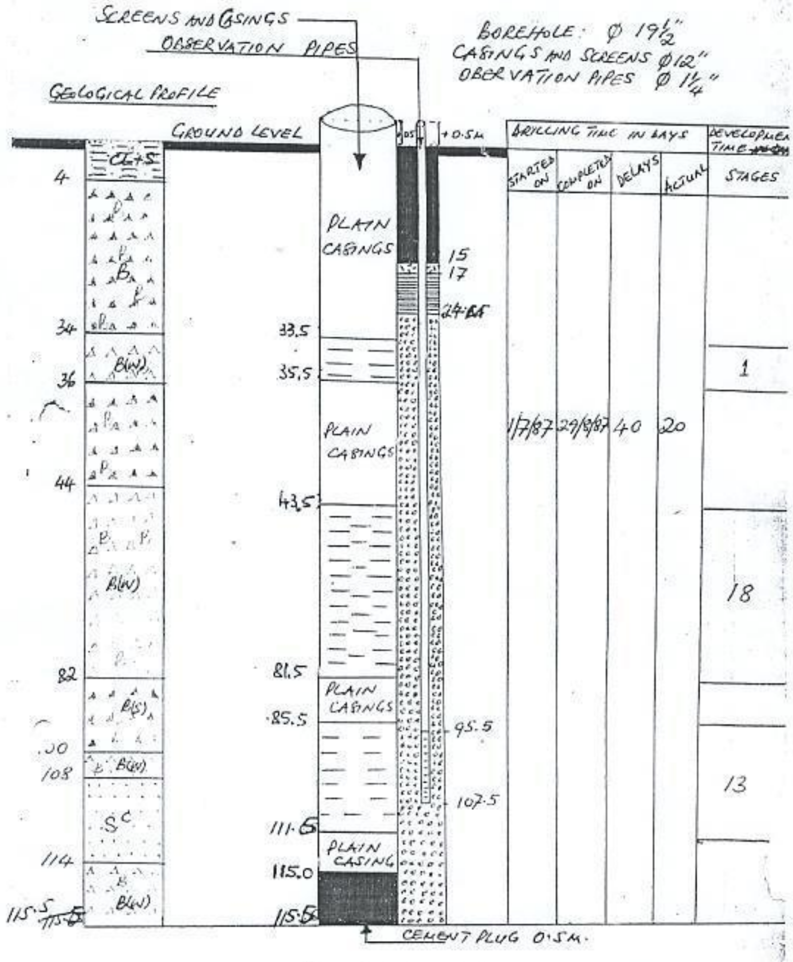
Cable-Tool to ______ ft. ins.

Coring-Diamond to ______ ft. ins.

Coring-Shrot to ______ ft. ins.

Abdallah

BH· AR 52/87 - ILBORU

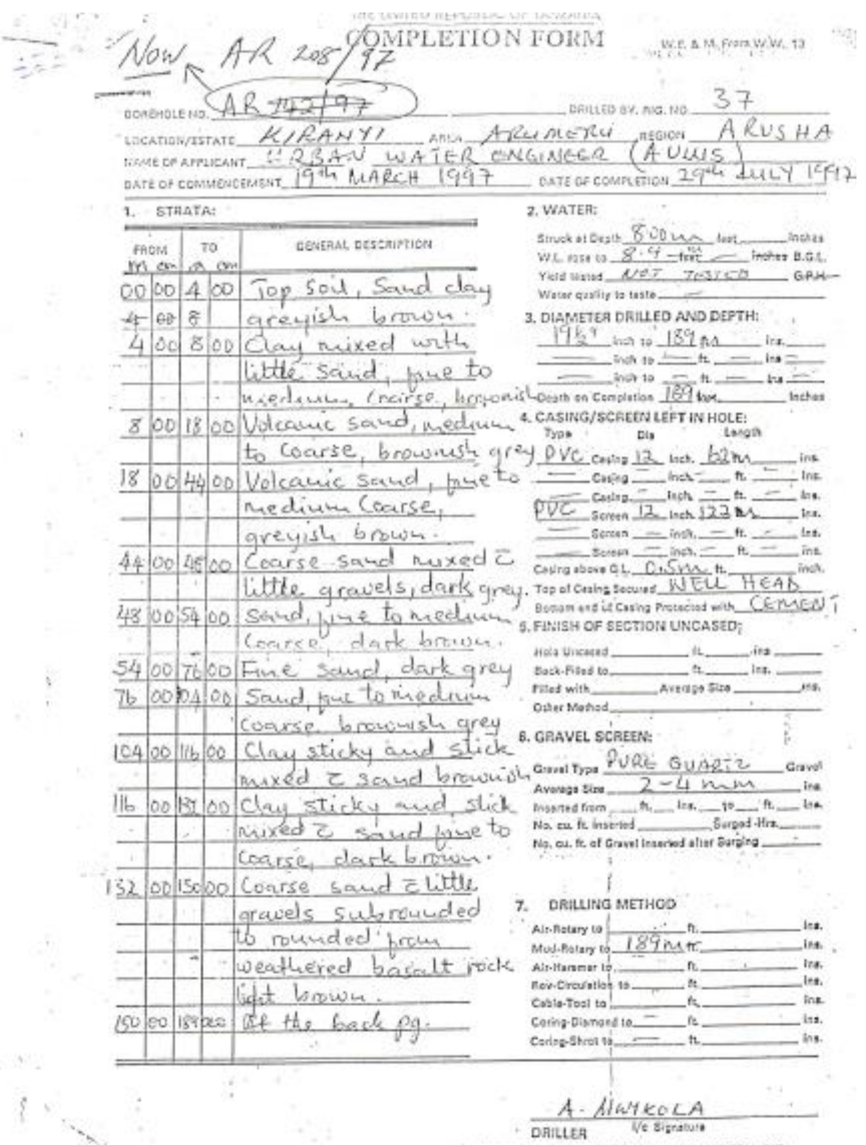


SYMBOLS USED

CL = CLAY
SF = SANDFINE
ΔB = BASALT WEATHERED
S+B = SAND WITH BASALT
T+B = TUFF-BASALTIC
S+B+T = TUFF-BASALTIC WITH SAND
SFC = SANDFINE TO COARSE
ΔB(S) = BASALT SOLID

■ CEMENTED ZONE
▨ LOCAL MATERIAL
▤ CLAY SEAL
▦ GRAVEL

DRAWN NOT TO SCALE
ALL DIMENSIONS ARE GIVEN IN METRES



THE UNITED REPUBLIC OF TANZANIA

Now ← AR 208/97

COMPLETION FORM

W.E. & M. Form W.W. 13

BOREHOLE NO. AR ~~142/97~~ DRILLED BY. RIG. NO. 37

LOCATION/ESTATE KIRANYI AREA ARUMERU REGION ARUSHA

NAME OF APPLICANT URBAN WATER ENGINEER (AUWS)

DATE OF COMMENCEMENT 19th MARCH 1997 DATE OF COMPLETION 29th JULY 1997

1. STRATA:

FROM m	FROM cm	TO m	TO cm	GENERAL DESCRIPTION
00	00	4	00	Top soil, Sand clay
~~4~~	~~00~~	8		greyish brown.
4	00	8	00	Clay mixed with little sand, fine to medium, coarse, brownish
8	00	18	00	Volcanic sand, medium to coarse, brownish grey
18	00	44	00	Volcanic sand, fine to medium coarse, greyish brown.
44	00	48	00	Coarse sand mixed c̄ little gravels, dark grey.
48	00	54	00	sand, fine to medium coarse, dark brown.
54	00	76	00	Fine sand, dark grey
76	00	104	00	Sand, fine to medium coarse, brownish grey
104	00	116	00	Clay sticky and stick mixed c̄ sand brownish
116	00	132	00	Clay sticky and stick mixed c̄ sand fine to coarse, dark brown.
132	00	150	00	Coarse sand c̄ little gravels subrounded to rounded from weathered basalt rock light brown.
150	00	189	00	Ref the back pg.

2. WATER:

Struck at Depth 8.00 m feet ____ Inches

W.L. rose to 8·4 m ~~feet~~ — Inches B.G.L.

Yield tested NOT TESTED ~~G.P.H.~~

Water quality to taste —

3. DIAMETER DRILLED AND DEPTH:

19½" Inch to 189 m Ins. ____

— Inch to — ft. — Ins —

— Inch to — ft. — Ins —

Depth on Completion 189 feet ____ Inches

4. CASING/SCREEN LEFT IN HOLE:

Type		Dia		Length		
PVC	Casing	12	Inch.	62 m	____	ins.
—	Casing	—	Inch.	—	ft. —	Ins.
—	Casing	—	Inch.	—	ft. —	Ins.
PVC	Screen	12	Inch.	123 m	____	Ins.
—	Screen	—	Inch.	—	ft. —	Ins.
—	Screen	—	Inch.	—	ft. —	Ins.

Casing above G.L. 0.5 m ft. ____ inch.

Top of Casing Secured WELL HEAD

Bottom and of Casing Protected with CEMENT

5. FINISH OF SECTION UNCASED;

Hole Uncased ____ ft. ____ ins ____

Back-Filled to ____ ft. ____ Ins. ____

Filled with ____ Average Size ____ ins.

Other Method ____

6. GRAVEL SCREEN:

Gravel Type PURE QUARTZ Gravel

Average Size 2-4 mm ins.

Inserted from ____ ft. ____ Ins. ____ to ____ ft. ____ Ins.

No. cu. ft. inserted ____ Surged Hrs. ____

No. cu. ft. of Gravel Inserted after Surging ____

7. DRILLING METHOD

Air-Rotary to ____ ft. ____ Ins.

Mud-Rotary to 189 m ft. ____ Ins.

Air-Hammer to ____ ft. ____ Ins.

Rev-Circulation to ____ ft. ____ Ins.

Cable-Tool to ____ ft. ____ Ins.

Coring-Diamond to — ft. ____ Ins.

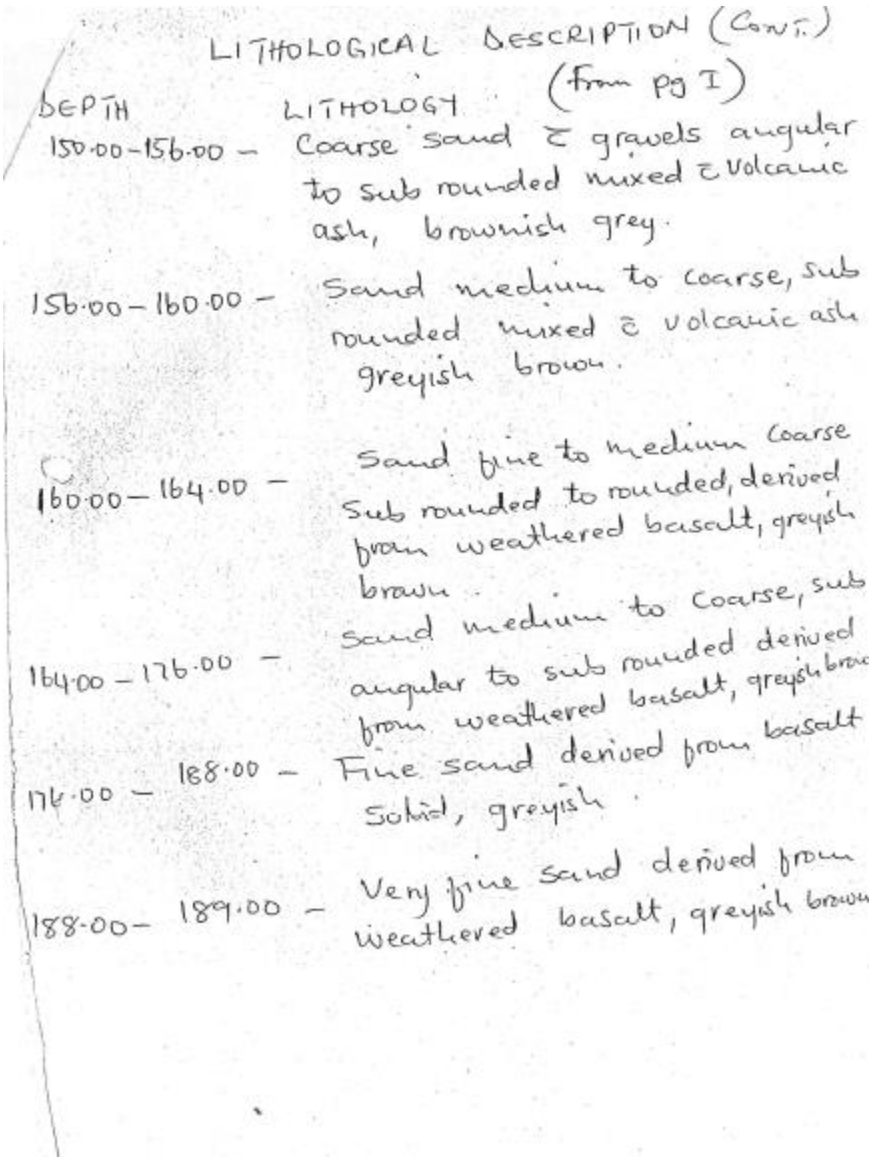
Coring-Shot to — ft. ____ Ins.

A. MWAKOLA

DRILLER I/c Signature

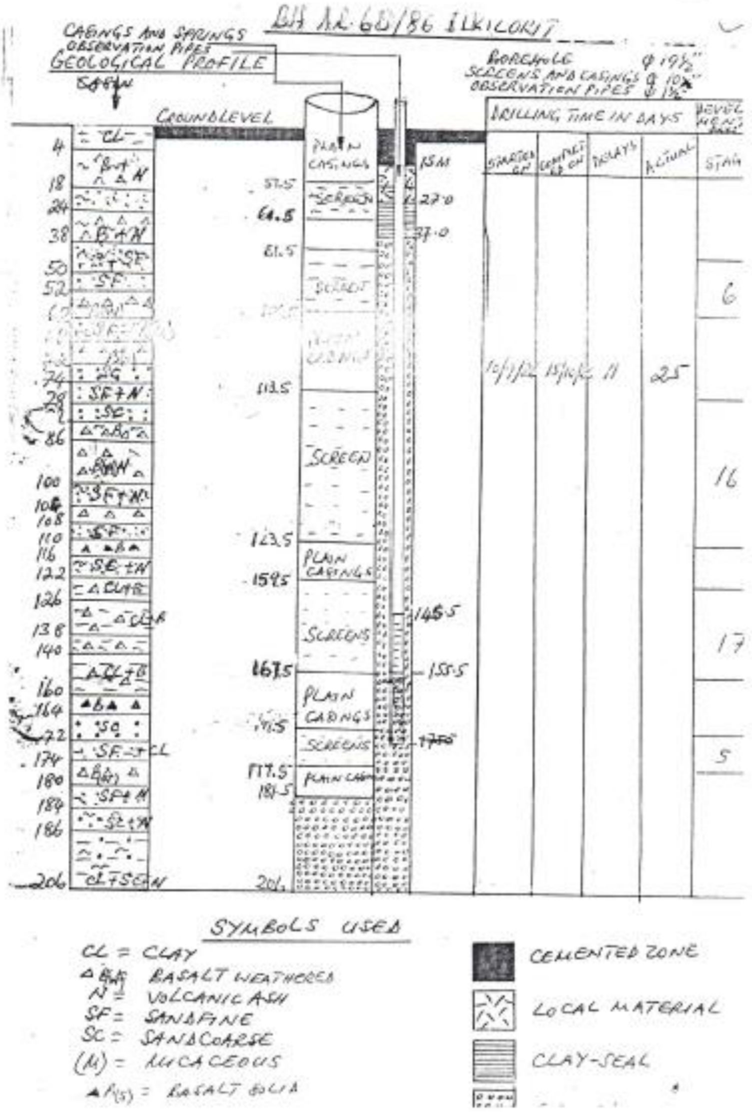
I AM SATISFIED THIS BOREHOLE HAS BEEN COMPLETED IN A WORKMANLIKE MANNER AND THAT THE BORING REGULATIONS HAVE BEEN COMPLIED WITH:

Ag. Regional Water Engineer



LITHOLOGICAL DESCRIPTION (Cont.)
(From pg I)

DEPTH	LITHOLOGY
150.00-156.00 –	Coarse sand c̄ gravels angular to sub rounded mixed c̄ Volcanic ash, brownish grey.
156.00-160.00 –	Sand medium to coarse, sub rounded mixed c̄ volcanic ash greyish brown.
160.00-164.00 –	Sand fine to medium coarse Sub rounded to rounded, derived from weathered basalt, greyish brown.
164.00-176.00 –	Sand medium to coarse, sub angular to sub rounded derived from weathered basalt, greyish brow
176.00 – 188.00 –	Fine sand derived from basalt solid, greyish.
188.00- 189.00 –	Very fine sand derived from weathered basalt, greyish brown


BH AR. 6D/86 ILKILORIT
CASINGS AND SPRINGS OBSERVATION PIPES
GEOLOGICAL PROFILE
BOREHOLE ф 19½"
SCREENS AND CASINGS ф 10"
OBSERVATION PIPES ф 1½"
GROUNDLEVEL
DRILLING TIME IN DAYS
STARTED ON
COMPLETED ON
DELAYS
ACTUAL
LEVEL
STAG
PLAIN CASINGS
SCREEN
SCREENS
PLAIN CASINGS
4
18
24
38
50
52
74
78
86
100
104
108
110
116
122
126
138
140
160
164
172
174
180
184
186
206
CL
B+A N
B+A N
SF
SF
SC
SF+N
SC
BAN
SF+N
SF
SF+N
CLAY
CLAY
SC
SF+CL
SF+M
SF+N
CL+SF+N
57.5
64.5
81.5
113.5
123.5
159.5
167.5
177.5
181.5
201
15M
27.0
37.0
145.5
155.5
10/1/82
15/2/82
11
25
6
16
17
5
SYMBOLS USED
CL = CLAY
△ BW = BASALT WEATHERED
N = VOLCANIC ASH
SF = SANDFINE
SC = SANDCOARSE
(M) = MICACEOUS
▲B(S) = BASALT SOLID
CEMENTED ZONE
LOCAL MATERIAL
CLAY-SEAL

LITHOLOGICAL DESCRIPTION FOR (BOREHOLE) BH

AR. 60/86 ELKLORITI ARUMERU DISTRICT.

ALL INTERVALS ARE IN METRES

0-4- Clay c̄ gravel fine brownish
4-6- Volcanic ash - greyyish brown
6-10- —"— —"— c̄
10-18- Volcanic ash c̄ gravel fine Basaltic
18-24- —"— —"— c̄ gravel coarse Basaltic
fine volcanic sand
24-26- Gravel coarse Basaltic c̄ volcanic ash
26-38- Volcanic ash greyyish brown c̄ gravel f
to coarse Basaltic
38-42- Volcanic ash greyyish
42-50- Volcanic ash, c̄ Volcanic sand greyyis
50-52- Sand fine to coarse Basaltic Black-brown
52-54- Gravel coarse Basaltic.
54-56- Gravel fine to coarse Basaltic c̄ volcanic a
[illegible]-58- Black-greyyish.
Gravel coarse basaltic c̄ Volcanic ash
greyyish brown.
58-62- Gravel fine to coarse basaltic c̄ volcanic a
62-66- Volcanic ash c̄ biotite and sand fine
basaltic - brownish grey.
66-68- Sand fine basaltic c̄ biotite black-greyy
68-72- Gravel fine to coarse basaltic black-greyyis
72-74- Sand coarse basaltic black-greyyish.
74-76- Gravel fine basaltic
76-78- Sand fine basaltic
78-80- Sand coarse basaltic c̄ volcanic ash.
80-82- Sand fine to coarse basaltic
82-100- Gravel fine to coarse basaltic c̄ volcanic
~~[illegible] Gravel fine to coarse —"— —"—~~
100-104- Volcanic sand c̄ Volcanic ~~sand~~ ash greyy
104-108- Gravel fine to coarse basaltic c̄ volcanic ash
108-110- Sand fine to —"— —"— —"— —"—
110-112- Gravel fine Basaltic, brownish grey in c
112-114- Gravel fine to coarse basaltic. black grey
114-116- Gravel fine basaltic c̄ biotite
116-120- Volcanic sand c̄ volcanic ash greyyish
120-122- Volcanic ash c̄ volcanic ~~ash~~ sand greyyish.
122-126- Gravel fine basaltic c̄ brownish clay
126-138- Clay brownish c̄ gravel fine to coarse basaltic
138-140- Gravel fine to coarse basaltic c̄ clay and volcan
140-160- Clay brownish c̄ gravel fine basaltic
160-164- Gravel coarse basaltic contaminated c̄ c
164-172- ~~Clay~~ Volcanic sand
172-174- —"— —"— c̄ Clay
174-180- Gravel fine basaltic
180-184- Volcanic sand c̄ volcanic ash greyyish
184-186- Sand coarse basaltic c̄ Volcanic ash.
186-204- Clay c̄ sand coarse basaltic c̄
volcanic ash.

Analysed by
A. K. H. [illegible]
COUNTERPART HYDROGEOLOGIST
ARUSHA URBAN WATER SUPPLY PROJECT

Checked by
DR. G. J. WALLASCH
CONSULTANT HYDROGEOLOGIST
ARUSHA URBAN WATER SUPPLY PROJECT.

Appendix 4: Stable isotopes analysis procedure

Water Sample Preparation

The standard volume for water samples is 1-1.4 mL in a 2 mL GC vial. Contact the SIF about low volume samples. Use vials with a write-on patch or use clear tape and permanent marker to label vials. Samples should be kept refrigerated and in the dark for long-term storage. Use minimal headspace for shipping and storing water samples. Additional preservation is not necessary. We do not accept samples preserved with mercuric chloride ($HgCl_2$) or poisoned with sodium azide (NaN_3).

Supplies

Submit samples in standard autosampler vials (volume: 2 mL, 12 mm O.D. x 32 mm length) with wide-mouth 10-425 screw caps and double coated (PTFE/silicone/PTFE) septa. Samples not submitted in autosampler vials will be charged a transfer fee

Organizing samples

For tracer studies, estimates on isotope values are required and samples must be organized by increasing enrichment.

Saline samples must be clearly marked with an estimate of the salinity. Organize saline samples in order of increasing salinity. Units of ppt or mS/cm are preferred. Organize water samples in order of increasing conductivity.

Turbid water samples or water samples containing precipitate must be filtered prior to analysis. If SIF determines a water sample requires filtering, a $5.00 fee will be charged per sample for this service.

The SIF only analyzes samples with a pH between 5 and 9. Samples outside this range must be neutralized prior to shipment to the SIF.

Shipping

Carefully package racks of vials in ziplock bags, small boxes, or their original boxes. Then package these sets in a larger sturdy box with styrofoam peanuts or bubble wrap. Make sure the samples are very secure; loose vials can break during shipping. If samples must be shipped with a refrigerant, be sure to insulate your samples from freezing. Avoid using dry ice as a refrigerant, as samples in direct contact with a refrigerant like dry ice will crack during shipping. Coolers will not be returned.

Analysis of Water

The SIF provides simultaneous analysis of ^{18}Oand D/H isotope ratios in liquid water samples using a Laser Water Isotope Analyzer V2 (Los Gatos Research, Inc., Mountain View, CA, USA). For ^{18}O and D/H at natural abundance, each sample is injected at least six times. The average of the last four injections is used for isotope ratio calculations. For enriched and saline samples, the number of injections is increased to ten. Sample isotope ratios are standardized using a range of reference waters which have been calibrated against IAEA reference waters (VSMOW, GISP, and SLAP). Precision for water samples at natural abundance is typically ≤ 0.3 per mil for ^{18}O and ≤ 2.0 per mil for D/H. Final $^{18}O/^{16}O$ and D/H values are reported relative to VSMOW.

Appendix 5: Radiocarbon Analytical procedure

$^{14}C/^{13}C$ Analysis

EIL converts clients samples (water DIC, organics, carbonates etc.) to pure carbon dioxide which is trapped in 6mm OD Pyrex glass tubes (Breakseal) which are then send to various Accelerator Mass Spectrometry Labs around the world for ^{14}C determination. A subsample of the evolved CO_2 is analyzed for ^{13}C for ^{14}C correction. The AMS facilities charge different amounts usually based on turnaround time.

Organic samples, and the organic portions of sediment samples, are treated using a variation of the well-established acid-alkali-acid (A-A-A) method. Acid removes extraneous carbonates, base removes adhered humates, and the second acid step assures removal of atmospheric carbon that may have been incorporated during the alkali treatment.

Gupta, S. K. and Polach, H. A., 1985. Radiocarbon Dating Practices at ANU. Handbook, Radiocarbon Laboratory, Research School of Pacific Studies, ANU, Canberra.

Stenström, K. E., Skog G., Georgiadou, E., Genberg, J., Johansson, A., 2011, A guide to radiocarbon units and calculations. Lund University, Lund, Sweden.

Direct AMS Radiocarbon Laboratory Procedures:

Carbon dioxide is reduced to graphite according to strictly defined protocols. Graphitized samples are measured on a state-of-the-art National Electrostatics Corporation 1.5SDH-1 Pelletron Accelerator. The accelerator produces measurements to 0.3% precision and accuracy. The dual ion-sources of the AMS instrument process graphite samples in 40-sample and 134-sample batches. By convention any result determined to be older than 45,000 YBP or Not Distinguishable from Background (NDFB) are noted as “>45,000” and negative activity as “Modern”.

All AMS measurements must pass stringent Quality Control (QC) tests before dates are reported. Standard reporting sheets list radiocarbon ages, delta ^{13}C values and the associated uncertainties.

Appendix 6: Principal data commonly required for developing a management strategy

Physical framework	◦ Topographic maps showing the stream drainage network, surface-water bodies, landforms, cultural features, and locations of structures and activities related to water ◦ Geologic maps of surficial deposits and bedrock ◦ Hydrogeologic maps showing extent and boundaries of aquifers and confining units ◦ Maps of tops and bottoms of aquifers and confining units ◦ Saturated-thickness maps of unconfined (water-table) and confined aquifers ◦ Average hydraulic conductivity maps for aquifers and confining units and transmissivity maps for aquifers ◦ Maps showing variations in storage coefficient for aquifers ◦ Estimates of age of ground water at selected locations in aquifers
Hydrologic information	◦ Precipitation and evaporation data ◦ Stream flow data, including measurements of gain and loss of stream flow between gauging stations ◦ Maps of the stream drainage network showing extent of normally perennial flow, normally dry channels, and normally seasonal flow ◦ Estimates of total ground-water discharge to streams ◦ Measurements of spring discharge ◦ Measurements of surface-water diversions and return flows ◦ Quantities and locations of interbasin diversions ◦ History and spatial distribution of pumping rates in aquifers ◦ Amount of ground water consumed for each type of use and spatial distribution of return flows ◦ Well hydrographs and historical head (water-level) maps for aquifers ◦ Location of recharge areas (areal recharge from precipitation, losing streams, irrigated areas, recharge basins, and recharge wells), and estimates of recharge
Chemical Framework	◦ Geochemical characteristics of earth materials and naturally occurring ground water in aquifers and confining units ◦ Spatial distribution of water quality in aquifers, both areally and with depth ◦ Temporal changes in water quality, particularly for contaminated or potentially vulnerable unconfined aquifers ◦ Sources and types of potential contaminants ◦ Chemical characteristics of artificially introduced waters or waste liquids ◦ Maps of land cover/land use at different scales, depending on study needs ◦ Stream flow quality (water-quality sampling in space and time), particularly during periods of low flow