ASSESSMENT OF GROUNDWATER RESERVES IN ARUSHA CITY AQUIFER USING A GROUNDWATER POTENTIAL MODEL

Case Study of Arusha City, Tanzania

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Masters in Integrated Water Resources Management (MIWRM) Dissertation
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By

Peter Pepa Bonus Mdalangwila

A Dissertation Submitted in Partial Fulfillment of the Requirements for the Degree of Masters in Integrated Water Resources Management (MIWRM) of the University of Dar es Salaam.

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September, 2008

CERTIFICATION

The undersigned certify that they have read and hereby recommend for acceptance by the University of Dar es Salaam a dissertation entitled: ***Assessment of Groundwater Reserves in Arusha City Aquifer Using a Groundwater Potential Model,*** in fulfillment of the requirements for the degree of Masters in Integrated Water Resources Management (IWRM)

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Date**:** …………………………………

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Dr. P. Ndomba

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Date: ……………………………..

DECLARATION

AND

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I, **Peter Pepa Bonus Mdalangwila**, declare that this is my own original work and that it has not been presented and will not be presented to any other University for a similar or any other degree award.

Signature:…………………………

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DEDICATION

This dissertation is dedicated to my late mother Consolata Bonus Mdalangwila, who passed away when I started my proposal writing, surely this was the darkest hours of my life, but I know the sun shall shine again.

You gave me life; put your love in my heart,

Now God has cut it too short, and it is time for us to part.

With my memories, each one I bless, I will keep you in my dreams,

Where you can let your love rest. I tried to fight reality,

but reality always wins. We were both so horribly cheated.

Mum I will love you forever.

ABSTRACT

The surface water resources of Arusha city are meager and the city is principally dependent on groundwater for its water supply. Currently the water supply for Arusha city which is sourced from springs, river intake and wells does not meet the demand, due to rapid population growth and the industrial development/urbanization. The sources comprise of wells, i.e. 41.7%, springs, i.e. 57.3% and river intake, i.e. 7.0%. Over the years, the groundwater exploration has focused singularly on boring wells to get water of which excessive abstraction caused lowering of groundwater table in the wellfield but no studies have been done on assessing the groundwater potential zones of the city.

The objective of this study is to assess the Arusha city groundwater reserve by mapping the groundwater potential zones and estimating the reserves. Groundwater Potential model, a modified DRASTIC model was used to map groundwater potential zones as well as potential borehole yield estimation. The model uses spatial data (Raster format) in Geographical Information System (GIS), where hydrogeologic parameters are analyzed to produce grid overlays. Determination of groundwater reserves and aquifer characterization were done also in ArcView (GIS) environment.

A Groundwater Potential map produced categorizes groundwater yield as very high, high, moderate, low and very low showing alluvial plains and red soils areas having very high groundwater yields. Total available groundwater reserves was estimated as 131,981 Million m^3/year while estimated groundwater yields from the model and actual borehole yield data are 1164.02 and 1088.16 Million m^3/year respectively.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYMS AND ABBREVIATIONS

a.m.s.l	Above mean sea level
AUWSA	Arusha Urban Water Supply and Sewerage Authority
DEM	Digital elevation model
DDCA	Drilling and Dam Construction Agency
DRASTIC	Department of Water Affairs and Forestry
ESRI	Environmental Systems Research Institute
GP	Groundwater Potential Model
IRA	Institute of Resources Assessment
MAR	Mean Annual Rainfall
MDGs	Millennium Development Goals
TIN	Triangulated Irregular Network
URT	United Republic of Tanzania
UDSM	University of Dar es Salaam

CHAPTER ONE

INTRODUCTION

1.0 General Introduction

Water is the most vital requirement for the mankind. Groundwater constitutes a major portion of the earth's water circulatory system known as hydrologic cycle. (Rao *et al.,* 2000). The cycle is driven by the energy of the sun and takes water from the large reservoirs of the oceans and transfers it through the atmosphere back to the oceans through various routes. When rain falls onto the land surface, a component infiltrates into the soil with the remainder evaporating, or running off to rivers. Water stored as moisture can be taken up by plants and transpired, or flow quickly (a few days or year) as interflow to a river channel. However, some of the water will infiltrate more deeply, eventually accumulating above an impermeable bed, saturating available pore space and forming an underground reservoir. This water is now called groundwater. Groundwater can be defined as sub-surface water that occurs in voids and permeable geologic formations. Groundwater is stored and transmitted through rocks. The rocks that store and transmit groundwater are called aquifers (MacDonald *et al*., 2005).

The importance of groundwater is often overlooked. It is a mysterious resource-out of site and out of mind. However, about 97 percent of all freshwater found on the Earth is stored underground (excluding frozen water glaciers) (MacDonald *et al.,* 2005). The resource is naturally fairly resistant to drought, storing up water in times of plenty, and releasing it in times of need; also the quality of the water tends to be good and is much less vulnerable to contamination than surface water. However the resource is not invulnerable: with the ability to pump out huge quantities of water, and the advent of particularly persistent contaminants, the resource needs to be protected and managed (MacDonald, Davies, Calow and Chilton 2005)

In arid and semi arid countries such as Tanzania, scarcity of surface water supply to meet demand has made groundwater an important resource. The present sources of water supply in Arusha city come from the wellfield, river intakes and springs. However the extent and characteristics of the aquifers which can supplement the supply now and in the future have not been studied. Although lack of such information in future will limit economic development and management of groundwater resources, attempt will be made in this study to assess the state of knowledge in the area. (Anna *et al.,* 2003)

The study of groundwater is vital since it plays an important role in the development of water resources in the world. In semi-arid regions where surface water availability is limited groundwater plays a great role in the supply of water for domestic and other economic uses.

1.1 Background of the Study Area

1.1.1 Location

Arusha city is located in the Northern part of Tanzania at latitudes 3°24'S and 3°18'S of the equator and longitudes 36°39'E and 36°44'E of Greenwich Meridian on the southern foot slopes of Mount Meru (4565m a.m.s.l) at about 30 km Southwest of its summit, which is an ancient volcano with an altitude of about 1300m a.m.s.l (Fig.1.1).

The city forms part of the Pangani River Basin.The basin covers an area of 42,200 km^2 (Rohr e*t al*., 2001). Its rivers and streams are important sources of water to the basin. It is bounded on the east by Nduruma River, and to the north by Arumeru district, on the west by Engare Olmotonyi River and Arumeru district and to the south by Simanjiro district. Themi River is the main river which flows almost through centre of the area from north to southeast. Its population as of 2003 census was over 282,712 inhabitants with a growth rate of 3.8% per annum (URT, 2003).

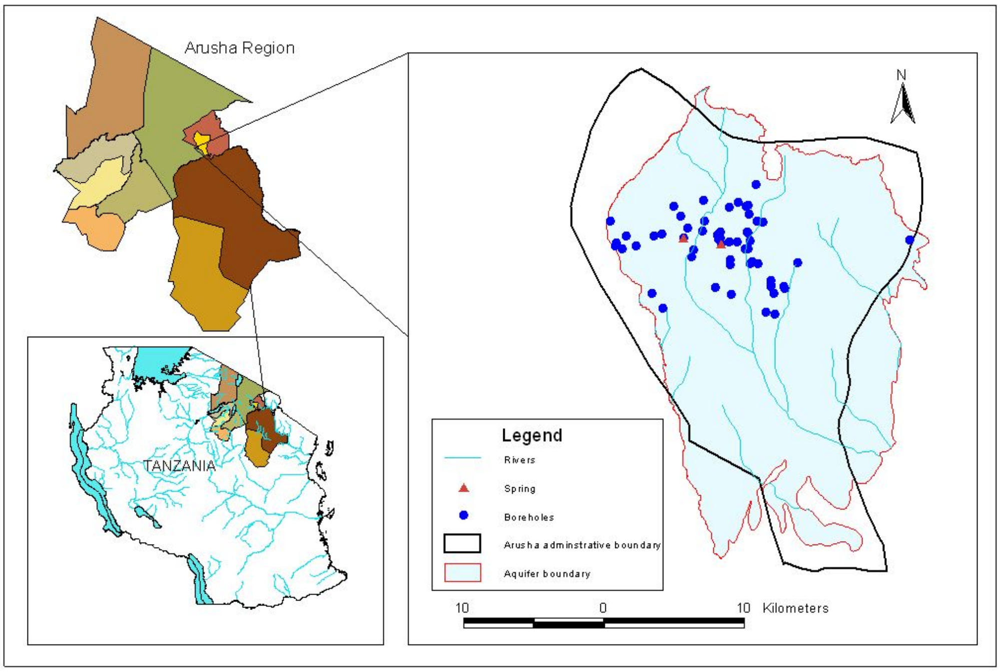


Figure 1.1 Location of the study area Arusha city

It is expected that by year 2015 there will be over 452,632 inhabitants due to urban migration. Likewise, industrial development and other human activities have increased water demand. This rapid growth of population, against the national rate of 2.091% per annum has resulted in growth of unplanned settlements and socio-economical problems. This implies that the current source of water will not satisfy the demand.

Arusha city is supplied with water from springs, wells and river intake (Fig.1.1). The spring sources include Olesha-Masama springs along Themi River located 4 km north of the city and "Ngarendolu Springs Located within the city. There are 15 deep wells (boreholes), 13 of which are located in the northern part of the city in Arumeru district and 2 boreholes located one within the city area and the other near Nduruma River along Moshi Arusha Highway in Arumeru district. These boreholes contribute nearly half of the daily water production whereas the springs and river intake contribute the other half. The production capacity fluctuates seasonally from an average of 36,000m^3/day in dry season to 56,000 m^3/day during the rainy season. This points to the fact that additional sources are required, to maintain adequate supply during dry seasons or incase of failure of rains as it happened in late1990s (Arusha Region Water Master Plan, 2000).

1.1.2 Topography and Drainage

The Arusha city lies on the northwestern part of the Pangani River Basin. It consists of gently slopping terrain dissected by the valleys of rivers Themi, Naura, and Ngarenarok, Kijenge and Goliondoi all of which converge to join Themi in the south. They generally run in the North-South and South-East direction from slopes of Mount Meru towards Shambarai Swamp and the Kikuletwa River where they join with rivers from Mount Kilimanjaro on their way to Indian Ocean, through Nyumba ya Mungu Dam, and Pangani where the Ruvu meets with Mkomazi River from South Pare Mountains.

Other features include two springs, which are the major collection points of spring water: Ngarenaro Spring located in the town centre and Olgilai Spring at the northeast boundaries.

1.1.3 Climate

Arusha city experiences almost a temperate climate. Volcano modified type of equatorial climate. Topography has a strong influence on the distribution of precipitation over the area. There are two rainy seasons occurring, the long rainy season lasting from March to May and the short rainy season from November to December. Mean monthly rainfall for the period 1993-2000 is 738mm. Rainfall occurs approximately fifty percent of the year, varying from a maximum monthly mean of 202mm in April to a minimum monthly mean of 4mm in August (U.R.T, 2003).

The mean annual temperature is about 20^0C with the absolute maximum and minimum temperatures of 33^0C in February and 4^0C in October respectively. The hottest month is March with an average of 21^0C and coolest month is July with an average temperature of 17^0C.

1.1.4 Geological Setting

The geology of the study area is in volcanic consisting of igneous rocks, which was formed when magma cooled and solidified (crystallized), which occurs either beneath or on the surface. The Mount Meru a stratovolcano built of both pyroclastic and lava material is one of the 20 volcanoes in the eastern part of the Great Rift Valley, stretching 6400 km from Jordan to Mozambique. The stratovolcano of Mount Meru has a symmetrical structure and its volcanic activity is very violent. Lava varies from thin to thick intrusive domes. Inside the main cone is a caldera (basin-shaped volcanic depression) of 3.5 km in diameter (Volcano World, 2005; Johansson e*t al.,* 2003).

The urban area of Arusha and part of Arumeru district is composed of Neogene volcanic rocks and sediments derived from decomposed weathered volcanic rocks. The main eruption centre for volcanic rocks Mt. Meru is made up of alternative layers of basalts, volcanic ashes and tuffs. Materials eroded from ash beds, agglomerates, tuffs and occasional lava flows were washed down the slope of Mount Meru as mud and debris forming a low gradient apron around the base of the mountain consisting of boulders, pebbles, cobbles and gravel in matrix clay (JBG *et al*., 1978, Johanson and Nilsson, 2003; Temba, 2004)

1.1.5 Hydrogeology

The rate of movement and amount of storage of groundwater in the volcanic areas like Arusha depend on the subsurface material. The classic sediments (Sand, gravel, boulders) in the northern part of the Arusha basin are filled with groundwater which drains off in a southern direction along the slope of Mt. Meru.

The main input to groundwater is precipitation (i.e. rainfall) and, to a minor extent, infiltration of water from surface water applications. Groundwater occurs in the alluvial, fractures and weathered zones of the basement rock (basalts) below the water table, under unconfined and semi-confined conditions.

The porosity and permeability can measure a material's capacity of yielding groundwater. The porosity is the percentage of the total volume of rock or sediment that is made up of voids or openings. Voids can be spaces between sedimentary particles, joints, faults, cavities and vesicles (voids created when gases left lava). The permeability is the ability of a material to transmit a fluid. (Tarbuck *et al.,* 2002)

1.1.6 Geomorphology

Geomorphologically the city lies on the southern slopes of Mount Meru (4,565m a.m.s.l) formed by volcanic activities. Likewise, the area is characterized by a number of volcanic cones, which are Themi hill (1,430m), Njiro Hill (1,350m), Suia Hill (1,450m) and Namasi Hill (1,550m). Lowland plains on the southern part extend to the south, east and west towards the Maasai steppe, Kilimanjaro International airport and Rift Valley respectively.

1.1.7 Land use and Land cover

The land use of the study area is characterized by a mixture of forest cover, agricultural activities and residential area. The northern part of the Nairobi-Moshi road hosts the wellfields which supply the city; and residential houses exist whereby activities such as plots for cattle's and growing vegetables and fruits. But the intensity of these houses decreases as you go further north while plot sizes increases. In the north part of the wellfields the major land use is agriculture and forestry while in the city periphery intensity of houses become higher with unpaved roads and in the far south population is highly scattered.
The main water bodies in the area are the Lake Duluti, Themi River, River Nduruma in the eastern part of the city and River Engare Olmotonyi in the west.

Arusha like any other expanding town in Tanzania is facing land degradation, destruction of biological diversity, disturbance of the ecosystem, and threatening water resources. Rainfall fluctuations and human interventions, through fire, overgrazing, encroachment, fuel wood, construction timber/poles, furniture's wood/timber, creates loss of about 0.5% of forest and 4.0% of grass cover annually. Newman and RÖmberg (1992) and Sandstrom (1995) reported that woodland and bush land covered 73% of catchment area in I960, but only 11% in 1990,

1.2 Problem Statement

The current water supply for Arusha city is mainly sourced from springs, river intake and wells which do not meet the demand. This is severely propagated with rapid population growth and the industrial development/urbanization. There are 15 deep wells (boreholes) used by Arusha Urban Water Supply and Sewerage Authority (AUWSA) to supply water in the city. 13 boreholes out of these are located in the northern part of the city in Arumeru district whereas one among the two is within the city centre and the rest is situated near Nduruma River along Moshi-Arusha Highway in Arumeru district. The daily average production is 36,000m^3/day during dry season and 56,000 m^3/day during the rain season. While the Water demand for the city is 60,435m^3/day. The sources comprise of wells, i.e. 41.7%, springs, i.e. 51.3% and river intake, i.e. 7.0%.

Likewise there is a lowering of groundwater table in the wellfield due to excessive abstraction, causing the wells to produce below capacity. If these situations persist, water shortages could become severe, especially during dry periods. With such trend the capacity of present wellfields will be overwhelmed hence there is a need to explore new potential wellfields for augmenting the water supply of the town.

Besides, prior studies in the area (Anna and Hakan, 2003) suggested that in the long run new sources of drinking water need to be developed, such as new wellfields

A proper assessment of the groundwater potential zones is lacking in most developing countries such as Tanzania (MacDonald *et al*., 2005). This means that the basis for proper planning/management of water resources is also lacking. Thus, assessing the groundwater reserves for Arusha town is needed so that groundwater resources sustain water supply. The study will use Groundwater Potential model (GP) to map the groundwater potential zones for locating boreholes/wellfields. The

GP- model is considered to be less expensive method since the required data is readily available in government offices/agencies (Kahimba, 2002).

1.4 Objectives of the Study

The overall objective of this study is to assess the groundwater reserves of Arusha city.

The specific objectives of the study include the following:

- Characterizing and mapping Arusha City Aquifer
- Mapping of the groundwater potential zones.
- Estimation of groundwater reserves available for Arusha city aquifer.

1.5 Significance of Study

The study will produce groundwater potential map that will help the Water managers and planners to allocate areas for drilling boreholes/welfields, which will complement Arusha city water supply. It is envisaged that the results of the study will allow planners to make more informed choices about water related development activities. In this regard the study will contribute towards the achievement of the Millennium Development Goals 7 (MDGs) targets 10 which stipulates that by 2015 the proportion of people without sustainable access to safe drinking water to be halved.

1.6 Dissertation structure

This dissertation comprises five chapters and several sections and sub-sections under each chapter.

Chapter one is introduction part, which brief discusses about the study area, problem statement, objectives and significance of the study.
Chapter two is devoted for literature review where groundwater matters were reviewed. Besides, the chapter reviews previous studies done in the study area and in Tanzania at large.

Chapter three covers the methodology used in the study that is Groundwater Potential model which was used for mapping the groundwater potential zones and various methods for determining the groundwater reserves.

Chapter four gives the results and discussions. It covers the results from aquifer characterization, mapping of potential groundwater zones and estimation of available groundwater reserve

Chapter five covers conclusions and recommendations. In this chapter conclusion is given according to the results obtained from the study, and recommendations are proposed with support from the conclusions made.

CHAPTER TWO

LITERATURE REVIEW

2.0 Introduction

According to MacDonalds *et al.,* (2005) groundwater is defined as subsurface water that is in voids and permeable geologic formations. Underground water occurs in geologic formations known as aquifers. These are the geologic layers that are filled with water and that can transmit enough water to supply a well under normal hydraulic gradients .Geologic materials can be classified as consolidated rock or unconsolidated (loose) sediment. Consolidated rock may consist of such materials as sandstone, shale, granite, and basalt. Unconsolidated sediments contain granular material such as sand, gravel, silt, and clay.

The four major types of aquifers are;

- Alluvium(sand, gravel, and silt deposited by a river)
- Sedimentary bedrock(consolidated sediments)
- Glacial sediments(unconsolidated material deposited by glaciers);and
- Igneous or metamorphic bedrock.

There are three factors that influence ground water occurrence. These are the hydraulic properties of geological formations, geological framework and climate. Hydraulic properties of geological formation are those properties governing ground water storage and transmission. These include pores, vesicle, lava tubes, (and tunnels), solutions cavities, bedding plane, foliation, faults, shear zones, unconformities and intrusive contacts. Some of these structures are primary that is, they were formed at same time as formation while secondary ones were formed after the formation. The generic term for the relative volume of geologic formation in which water can be stored is porosity regardless whether that volume consists of pores or other types of openings (Akpofure *et al*., 2002).

Geological framework includes topography, type of geological formation, physical and chemical characteristics of surficial or unconsolidated deposits overlaying bedrock.

Climate factor includes precipitation, temperature, atmospheric humidity and pressure, wind velocity and pan evaporation

2.1 Groundwater Flow Equations

2.1.1 Steady State Saturated Groundwater Flow

Transient flow in groundwater systems can be described by equations that are derived by combining Darcy's law and statement of mass conservation or mass balance (Continuity equation). This latter statement states that mass inflow rate minus outflow rate equals rate of change of mass storage. Consider this statement as it applies to the small cube referred to as the control volume (CV) of porous material of unit volume where Δx, Δy, Δz = unity. If the velocities of flow in Cartesian coordinates x, y, z are V_x, V_y and V_z by considering mass flux through the sides of the control volume we get equation of continuity for fluid flow as:

$$\frac{\partial(\Delta m)}{\partial t} = \left[\frac{\partial(\rho Vx)}{\partial x} + \frac{\partial(\rho Vy)}{\partial y} + \frac{\partial(\rho Vz)}{\partial z} \right] \tag{2.1}$$

At steady state $\frac{\partial(\Delta m)}{\partial t} = 0$

Hence equation 1 becomes

$$\frac{\partial(\rho Vx)}{\partial x} + \frac{\partial(\rho Vy)}{\partial y} + \frac{\partial(\rho Vz)}{\partial z} = 0 \tag{2.2}$$

By assuming fluid to be incompressible, ρ remains constant. Equation 2.2 can thus be written as

$$\frac{\partial Vx}{\partial x} + \frac{\partial Vy}{\partial y} + \frac{\partial Vz}{\partial z} = 0 \tag{2.3}$$

From Darcy's law

$$Vx = -\mathrm{K}x \frac{\partial h}{\partial x} \tag{2.4}$$

Substituting equation 2.4 into equation 2.3 and assuming the aquifer to be homogeneous and isotropic, we get Laplace's equation as follows:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} = 0 \tag{2.5}$$

For unsteady groundwater flow, the rate of change of mass $\rho S_s \, {\partial h}/{\partial t}$ gives the following Diffusion equation (Transient flow)

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}+\frac{\partial^2 h}{\partial z^2}=\frac{S_s}{K}\frac{\partial h}{\partial t}=\frac{S}{T}\frac{\partial h}{\partial t} \tag{2.6}$$

By considering recharge, the general groundwater flow equation can be written as

$$\frac{\partial}{\partial x}\left(T_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T_y\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(T_z\frac{\partial h}{\partial z}\right)=S\frac{\partial h}{\partial t}-q_{x,y,z,t} \tag{2.7}$$

Where:

T=Transmissivity (Kh for unconfined or Kb for confined cases)

S = Storage coefficient (= S_y for unconfined or S_c for confined cases)

h= Unconfined aquifer thickness

q=Recharge rate.

2.1.2 Steady Radial Flow into Wells

Wells are commonly used to extract water from aquifers. Considering a well completely penetrating a confined aquifer of thickness B, with its original piezometric head H and is discharged at a constant rate Q. The well arrangement is shown in figure 1 below.

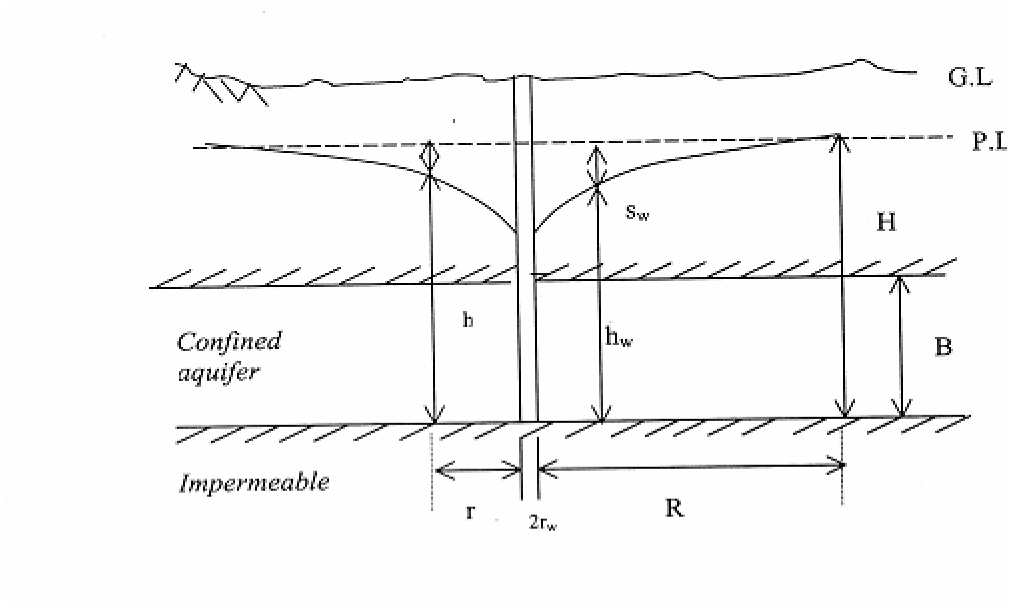


Figure 2.1 Radial flow in a confined aquifer (adopted from Todd, 1964)

The radial velocity of flow towards the well according to Darcy's law is

$$V_r = \mathrm{K}\frac{\partial h}{\partial r} \tag{2.8}$$

The cylindrical surface through which the flow occurs is $2\pi rB$. Discharge, Q will be given by the equation

$$Q = (2\pi r\mathrm{B})(\mathrm{K}\frac{\partial h}{\partial r}) \tag{2.9}$$

Integrating and simplification of equation 2.9 gives an equilibrium equation for steady flow in confined aquifer (Thiem's equation)

$$Q = \frac{2\pi T(s_1 - s_2)}{\ln(r_2/r_1)} \text{ or } Q = \frac{2\pi TS_W}{\ln(R/r_w)} \tag{2.10}$$

Equation 2.10 can be used to find the value of aquifer transmissivity, T.

Wheres:

S_1 Drawdown observed at distance r_1 from pumping well.

S_2 : Drawdown at distance r_2

r_1 Distance at point 1

r_2 Distance at point 2

S_w Drawdown observed in the pumping well

r_w Distance of r_1, taken at the radius of the pumping well.

R is the distance of r_2 taken at large distance from pumping well where S_2 is about equal to zero.

2.1.3 Flow in Leaky confined aquifer

Equations are derived considering the confined aquifer being homogeneous, isotropic and with flow in the horizontal plane only. Assuming W to be the penetration rate, mass balance of the system gives

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}+\frac{W}{bK}=\frac{S}{bK}\frac{\partial h}{\partial t} \qquad (2.11)$$

But $W=\dfrac{K_a(h_a-h)}{b_a}$ (2.12)

Where:

W= Percolation rate

b= thickness of aquifer

b_a =thickness of aquitard

K=hydraulic conductivity of aquifer

K_a=hydraulic conductivity of aquitard

h_a =head at point h_a

h =head at point h

Equation 2.11 becomes

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{K_a}{K}\frac{(h_a - h)}{b.b_a} = \frac{S}{bK}\frac{\partial h}{\partial t} \quad (2.13)$$

Leakage factor, B is given as

$$B = \sqrt{\frac{Kbb_a}{K_a}} \quad (2.14)$$

Hence by substituting leakage factor in equation 2.12 we get the equation of leaky aquifer in confined case as:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{h_a - h}{B^2} = \frac{S}{bK}\frac{\partial h}{\partial t} \quad (2.15)$$

And for unconfined case the equation is written as:

$$\frac{\partial}{\partial x}(h\frac{\partial h}{\partial x})+\frac{\partial}{\partial y}(h\frac{\partial h}{\partial y})+\frac{\partial}{\partial z}(h\frac{\partial h}{\partial z})+\frac{W}{K}=\frac{S_y}{K}\frac{\partial h}{\partial t} \tag{2.16}$$

2.2 Aquifer Recharge Mechanism

2.2.1 General

Groundwater recharge can be defined as the replenishment of an aquifer with water from the land surface usually expressed in mm/year. Main sources of recharge to an aquifer are precipitation, and stream flow (influent seepage) while those of groundwater discharge are effluent seepages into streams, lakes, springs, evaporation and pumping (Gupta, 1991). Artificial recharge is also another method used to artificially replenish an aquifer.

The main factor that influences groundwater recharge from precipitation is climate (temperature, humidity, and potential evapo-transpiration). Other factors are vegetation, soil and relief.

Calculation of annual groundwater recharge is done by using the Soil Moisture Accounting Model, water balance method, tracers and application of Darcy's law.

2.3 Evaluation of Pumping Tests Data and Determination of Aquifer Parameters

2.3.1 Introduction

Earth materials (soils or rocks) contain pores that can store water. When these materials are saturated with water they are regarded as saturated formations. Based on water movement, saturated formations can be classified into four categories:

Aquifer- defined as a geological unit that can store and transmit water at rate fast enough to supply reasonable amounts to wells. Unconsolidated sand and gravels, sandstones, limestones and dolomites, basalt flows, and fractured plutonic and metamorphic rocks are examples of rocks units known to be aquifers (Fetter, 2001).

Aquitard - a saturated but poorly permeable stratum that impedes groundwater movement and does not yield water freely to wells, that may transmit appreciable water to or from adjacent aquifers and, where sufficiently thick, may constitute an important groundwater storage zone; sandy clay is an example (Todd e*t al.,* 2005).

Aquiclude – a saturated but relatively impermeable material that does not yield appreciable quantities of water to wells; clay is an example (Todd and Mays, 2005).

Aquifuge - A relatively impermeable formation neither containing nor transmitting water; solid granite belongs in this category (Todd and Mays, 2005).

Groundwater aquifers are classified into two main categories namely unconsolidated aquifers and Consolidated fractured aquifers. In each of the two, aquifers are categorized as confined, unconfined or leaky.

Confined aquifer: Is an (artesian or pressure aquifer) aquifer, which is confined between two impervious beds such as aquicludes or aquifuges. Pressure of water is usually higher than atmospheric; hence the piezometric level is higher than the top level of the aquifer. Recharge takes place in areas where it is exposed to the ground surface.

Unconfined aquifer: An unconfined aquifer (water table aquifer), is an aquifer that is bounded below by an impermeable layer, but contain free water surface (water table) on the upper part. Its water table is free to rise and fall. Recharge of this aquifer takes place through infiltration of precipitation from ground surface.

Leaky aquifer (semi-confined aquifer): Leaky aquifer is a confined aquifer whereby either or both of its confining beds are aquitards. Water is free to move through an aquitard either upward or downwards. Leaky aquifer may form a multi-layered aquifer system by an inter-bedded system of permeable and less permeable layers in deep sedimentary basins.

2.2.3 Aquifer characteristics

Major parameters in aquifer characteristics are Transmissivity (T) and Storativity (S) or Storage Coefficient.

Transmissivity (T) can be defined as a measure of the amount of water transmitted horizontally by the full saturated thickness under a hydraulic gradient of 1. It is a product of the aquifer material's hydraulic conductivity and the aquifer thickness, and provides a measure of how easily groundwater moves in the aquifer whereas the storage coefficient reflects the volume of water available in the aquifer.

$$T = Kb \tag{2.17}$$

Where: T = Aquifer Transmissivity (m /d)

K = Hydraulic Conductivity (m/d)

b = Aquifer Thickness (m)

Storativity (S) is the volume of water that an aquifer will absorb or expel from storage per unit surface area per unit change in head.

For unconfined aquifer storativity is measured per unit decline of water table, taken as the product of Specific Storage (Ss) and aquifer thickness.

Therefore,

$$\text{Storativity } S = S_y + hS_s \tag{2.18}$$

Where: S_y = Specific Yield

h = Thickness of Saturated zone

S_s = Specific Storage

For confined aquifer Storativity is measured per unit change of potentiometric surface.

$$\text{Hence, Storativity, } S = S_s.b \tag{2.19}$$

Where: S = Storativity

S_s = Specific Storage

h = thickness of confined aquifer

Other physical properties of aquifer are defined below:

Specific storage (S_s): volume of water released by unit volume of aquifer from storage per unit decline in hydraulic head.

Specific yield (Y): is the volume of water that unconfined aquifer releases from storage per unit surface area of aquifer per unit decline in level of water table.

Hydraulic conductivity (K): is the volume of water that moves through porous medium in unit time under a unit hydraulic gradient per unit area measured at right angles to the direction of flow.

For a given aquifer, the values of T and S depend on aquifer thickness, hydrologic conductivity and hydraulic gradient. Hence in order to understand these parameters we need to know the geology, and perform pumping test of the aquifer.

2.3.2. Aquifer Identification from Time Drawdown curves

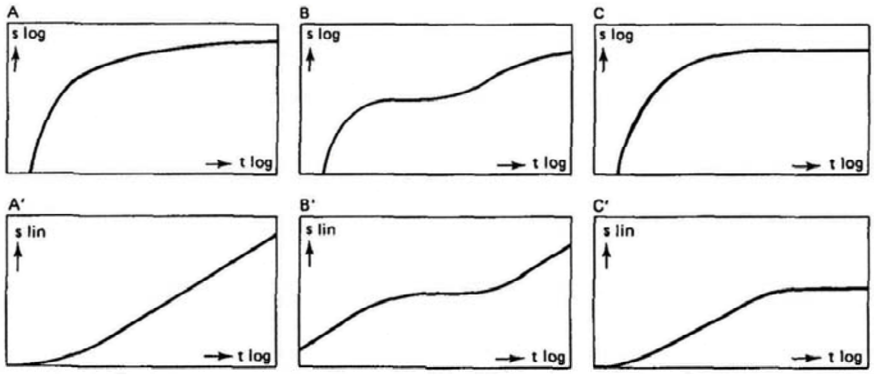
According to Kruseman e*t al.,* 1994 the Time-draw down plot curves for aquifers when are plotted from pumping test data. The produced graphs were compared with log-log and semi-log plots of the theoretical time-drawdown relationships as a result the following curves properties are reveled;

In an ideal confined aquifer (homogeneous and isotropic, fully penetrating, small diameter well).The drawdown follows the Theis's curve. That is when viewing the semi-log plot the time–drawdown relationship at early pumping times is not linear, but it becomes linear at later pumping times (Fig. 2.2 A and A').

The curves for the unconfined aquifer demonstrate a delayed yield. At early pumping times log-log plot follows the typical Theis curve. In the middle of the pumping duration, the curve flattens, which represented the recharge from the overlaying, less permeable aquifer, which stabilizes the drawdown. At later times the curve again follows a portion of the theoretical Theis curve. The semi-log plot is even more characteristics; it shows two parallel straight-line segments at early and later pumping times (Fig.2.2 B and B').

Whereas in a leaky aquifer the curves at early pumping times follows the Theis's curve that is, it increasing at the middle and more water from the aquitard reaching the aquifer. At later pumping times (Fig.2.2.C and C').

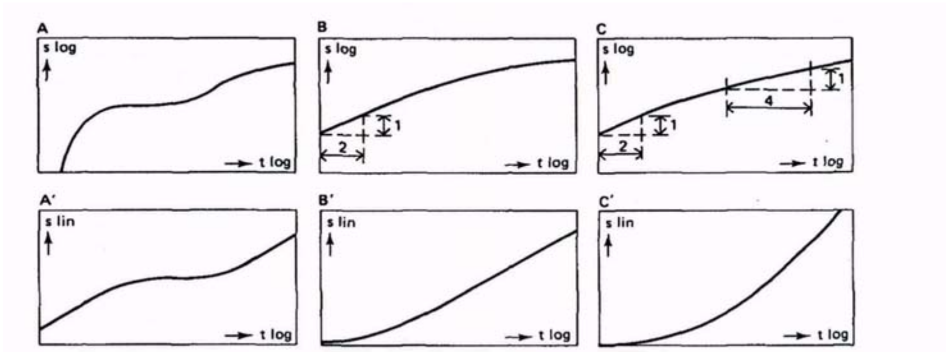
In case of confined fractured aquifer (consolidated fractured aquifers) with double porosity, the curves at early pump draw water from the fractures with high permeability and low storage. At this stage the curve rises, but when water in the fractures is finished the curve drops at the middle stage. Whereas at late stages the storage from the matrix block feed the fractures, hence stabilizes. This is due to the fact that once water in the aquifer is pumped more water from the aquitard enters the aquifer making the curve to rise. At later stages water pumped is from leakage through aquitard and flow reaches steady state. The drawdown at this stage stabilizes; hence the curve flattens (Fig. 2.3).



Confined aquifer unconfined aquifer, delayed yield leaky aquifer

Parts A and A’: Confined aquifer
Parts B and B’: Unconfined aquifer
Parts C and C’: Leaky aquifer

Figure 2.2 Log-log and semi-log plots of the theoretical time-drawdown relationships of unconsolidated aquifers. (Kruseman *at el.*, 1994)



Confined aquifer unconfined aquifer leaky aquifer

Parts A and A’: Confined fractured aquifer, double porosity type

Parts B and B’: A single plane vertical fracture

Parts C and C’: A permeable dike in an otherwise poorly permeable aquifer

Figure 2.3 Log-log and semi-log plots of the theoretical time-drawdown relationships of consolidated fractured aquifers. (Kruseman et al., 1994)

2.3.4 Analysis of Pumping Tests Data and Evaluation

A pumping test can be defined as means by which the characteristics of a ground water flow regime below a particular area may be determined under controlled conditions (Kruseman and deRidder, 1990).

Pumping tests are commonly used to better understand the aquifer system, to quantify hydraulic characteristics and to assess yield. However, to determine the hydraulic characteristic as s well as the relationship between yield (pumping rate) and drawdown, data over long time periods are required (Solomon *et al.*, 2005).

Specifically it is done in order to determine aquifer characteristics (transmissivity, hydraulic conductivity, storativity, and yield), to determine performance characteristics of the well and estimation of well deficiency under different pumping rates (Kruseman and deRidder, 1990).

2.3.5 Main Types of Pumping Test

Two types of pumping test can be distinguished namely Step down test and Constant discharge test.

Step down test is used to evaluate well performance under varying discharge rates. It helps to estimate aquifer transmissivity and aquifer capacity.

Constant discharge test is used for evaluation of well performance under constant discharge rates. The method can be used to determine nature of aquifer (confined, unconfined or leaky), aquifer characteristics and geometry, and to predict long term aquifer yield and well performance

During pumping test the following measurements should be taken; the discharge rate, record of time during pumping phase, record of time during recovery phase, water levels during pumping phase, water levels during recovery phase and the water quality of the discharged water.

According to Kruseman and deRidder (1994), when performing pumping test the piezometer for taking measurements is normally placed in an observation well at an average distance not more than five times the aquifer thickness.

Pumping rate and duration for pumping

While doing the pumping test, an optimum pumping rate is advised. Pumping at a very high rate may cause water loss, while very low pumping rate may cause the drawdown curve to be too gentle.

Normally, at the first stage of pumping the aquifer experiences unsteady state condition. After some time a steady state condition may be attained. This may take from few hours to even weeks depending on the response of the aquifer to pumping. Pumping test may be stopped even before attaining steady state. However a steady state condition i.e recommended since during data analysis simple steady state equations can be used to get a more reliable result. (Kahimba 2002)

2.3.6 Data Analysis for Determination of Aquifer Characteristics

The analysis of data depends on aquifer condition such as aquifer homogeneity, isotropic or anisotropic conditions, and whether the aquifer is confined, unconfined or leaky. The selection of method to be used will also depend on whether steady state conditions were attained during pumping.

Example, Theim's method is mainly used to analyze data for steady state flow conditions, while for unsteady state condition Thies's method is used as a basic theoretical model (Chow, 1964).

Common methods used for analysis are (i) graphical methods where data curves are superimposed on type curves, and (ii) analytical methods using computer software (example Aquifer Test Software Version 2.5).

2.4 Estimation of Groundwater Reserves

2.4.1 Introduction

The efficient management of groundwater reservoir is more complex than that of surface water. Information is required about variations in permeability and the storage capacity of rocks, the sources of inflow and the outflow. A wide range of water levels is necessary to derive the greatest benefits from storage available.

The total groundwater resource of an aquifer can be divided into two components: dynamic or replenishment resource, and static or storage resource. Static resources represent water lying in the aquifer below the principal natural outlets. These resources are not depleted naturally in a drought unless the aquifer is exploited by 'aquifer mining'. Estimation of static reserve depends on determination of saturated aquifer thickness and the coefficient of storage.

The dynamic resource represents the safe yield of the aquifer. According to Subramanya, (1994), Safe Yield is defined as the maximum rate at which the withdrawal of groundwater in a basin can be carried without producing undesirable results. Dynamic resources depend upon annual infiltration to the aquifer and can be equated with long-term mean infiltration.

2.4.2 Estimation by Water Balance method

The assessment of groundwater resource is often associated with completing water balance for the watershed. Equation of water balance in a watershed can be given as

$$P = E + SR + GR \pm Q \pm S \qquad (2.20)$$

Where: P = precipitation

E = actual evaporation

S_R = direct runoff and inter flow

G_R = groundwater discharge

Q = net groundwater flow through discharges

S = change in groundwater storage

When observations are made for a period of years, change in groundwater storage, S becomes less significant. Hence the net groundwater flow represents main part of groundwater resources.

The equation now becomes: $Q = P - E - S_R - G_R$ (2.21)

2.4.3 Measurement by Lysimeters

Infiltration of rainfall can be measured using instruments known as Lysimeters of infiltration gauges. The amount of infiltration measured can be used to estimate groundwater reserves. However, results from infiltrating gauges are unlikely to be representative on a regional scale hence the method is not commonly used.

2.4.4 Estimation of Safe Yield by Water Level Fluctuations

If water is abstracted from a confined aquifer at different rates over a number of years the hydraulic gradient can be related to the quantity of water abstracted. The groundwater level (piezometric surface) forms a linear relationship that can be used to determine the safe yield of the aquifer.

Water level can also be determined by fitting water level recorders on wells in the respective aquifer. Safe yield can be estimated by multiplying average annual fluctuations with the area extent of the aquifer and specific yield or storage coefficient (S).

$$\text{Safe Yield} = \text{Area x well level fluctuation x S} \tag{2.22}$$

2.4.5 Estimation of Total Reserve by Aquifer Porosity

This method is used to determine total available groundwater reserves as specific yield (unconfined aquifer) or storage coefficient (confined aquifer) the total volume of aquifer material. According to Kumar et al., 2002 the total volume of groundwater stored in aquifer material is estimated by multiplying average aquifer porosity to the volume of the aquifer material:

$$Q = \text{Area x Aquifer thickness x Porosity} \tag{2.23}$$

= Total volume of aquifer material x average aquifer porosity

2.4.6 Estimation using Aquifer Hydraulic Parameters

Equations can be derived that relate infiltration to rainfall. General equation of groundwater flow through an aquifer is given as:

$$Q = TiW = KiA – KiWh \tag{2.24}$$

Where: Q = total flow rate

T = aquifer transmissivity

i = hydraulic gradient

W = width of the aquifer at right angles to the flow direction

h = depth of the aquifer

Using borehole data and aquifer boundary map, values of transmissivity, width and slope of water surface/ piezometric surface can be used to determine amount of water infiltrating into the aquifer.

2.4.7 Prediction of groundwater potential zones using Groundwater Potential model (GP)

GP-model is a model used to evaluate groundwater potential zones of an aquifer using hydro-geologic settings derived from the region. According to Sener *et al.,* (2004) and Khairul *et al.,* (2000), the model uses numerical ranking system that assigns relative scores (weights) to these eight parameters for prediction and identification of groundwater potential zones in the study area. The model is a modified DRASTIC model, which is used to evaluate water pollution potential by The Environmental Agency of The United States of America (Aller *et al.,* 1985).

Based on the settings, formula for GP - Model is given as:

$$\mathbf{GP = R_f + L_t + L_d + L_u + T_e + S_s + D_d + S_t} \tag{2.25}$$

Where:

R_f = mean annual rainfall (mm/year)

L_t = lithology

L_d = lineament density (km/km^2)

L_u = land use

T_e = topography elevation (m)

S_s = slope steepness (%)

D_d = drainage density (km/km^2)

S_t = soil type.

- Annual Rainfall (R_f): mean annual rainfall distribution determines the amount of water entering the aquifer through groundwater recharge.
- Lithology (L_t): determines subsurface geology of the area. Quartz and granite materials for example store less water while alluvium materials store more.
- Lineament Density (L_d): Presence of fracture networks in the basement rocks gives higher values of fracture length per unit area. Higher score values of L_d depict occurrence of large groundwater storage. In general, lineaments acts as conduits for groundwater flow, and hence are hydrogeologically significant (Solomon *et al.,* 2005).
- Land use (L_u): Use of land on the area affects the surface runoff and infiltration of water. Wetland and agricultural areas are good potential zones for groundwater while cleared land and urban areas are low groundwater potential zones since paved and bare lands facilitate more surface runoff than infiltration.
- Topography Elevation (T_e): These represent elevation of land surface with respect to the datum. Flat topography has higher potential of groundwater while mountainous topography is less susceptible to contain much groundwater. Topographic data is a vital element in determining the water table elevation (Sener, Davraz and Ozcelik, 2004).
- Slope steepness (S_s): surface slope of the area is expressed in terms of percentage of slope gradient. Higher inclinations have low score values hence they are zones of low groundwater potential.

- Drainage density (D_d): the drainage density for each sub catchments is expressed in km/km2. Areas with low drainage density collects less surface water, hence allow more water to infiltrate deep into the aquifer.

- Soil type (S_t): Soil is the uppermost portion of the unsaturated zone. Areas with clay soil have low score weights while those with sand and coarse sandy clay soils have higher score values; hence they are good potentials for groundwater.

The final outputs of GP-model are reclassified into five groups based on the quantile classification method, ESRI 1996. The potential zones are classified as very high, high, moderate, low and very low. From model statistics, estimate of groundwater yield of the aquifer is also presented with estimated groundwater yield in m^3/hour/well.

2.4.8 Database Building and Analysis to Determine Model Parameters

Model flow chart

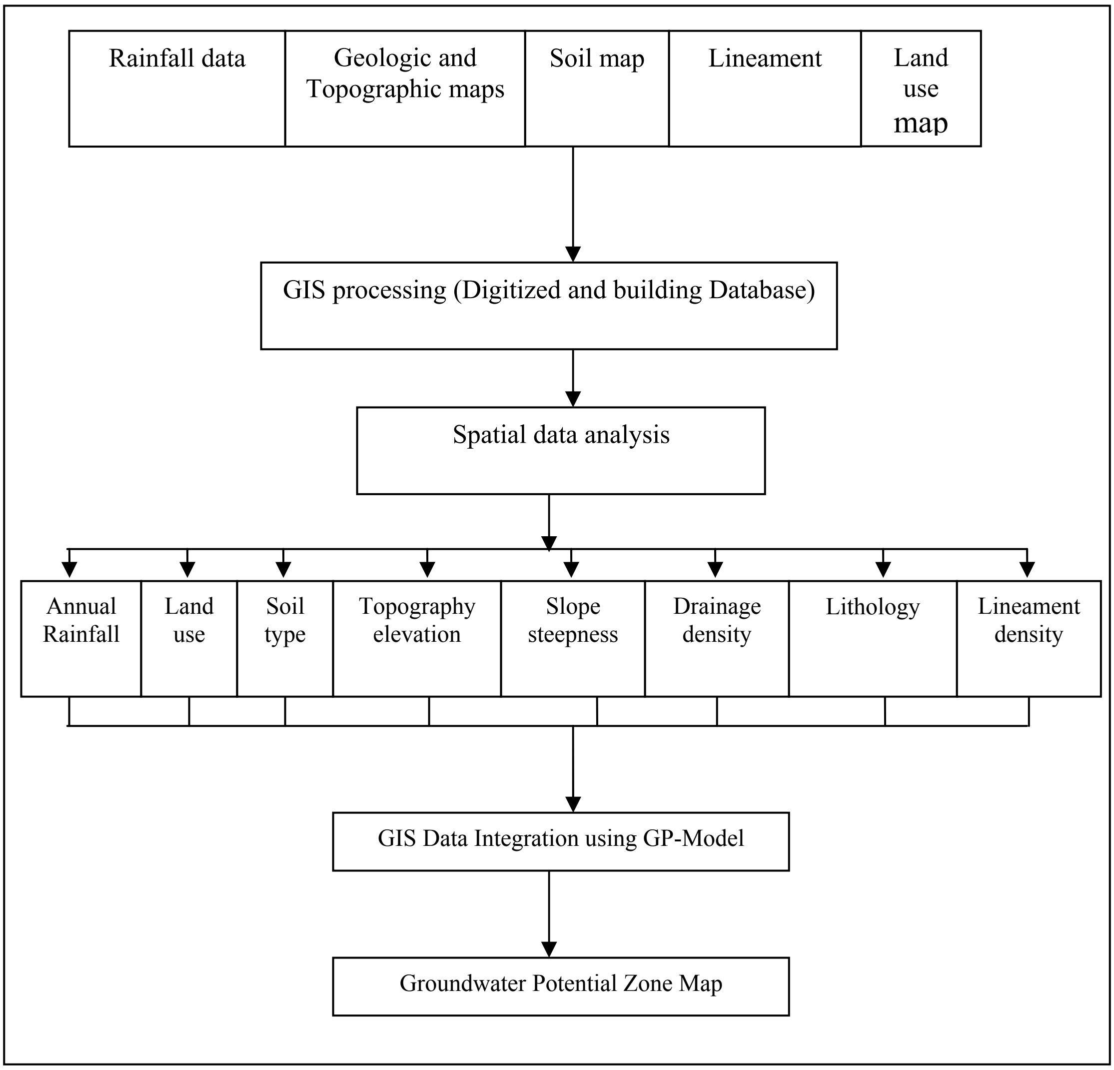


Figure 2.4 GP-model methodology flowcharts courtesy of Khairul, *et al,* 2000

Figure 2.4 shows flow-chart for analysis with GP - Model and data requirements for determination of model parameters. The appropriate data compiled together in a GIS database. Aim to produce derived layers that further are used for integration in the GP-model.

2.5 Relative Error Calculation

For a given an actual value (observed) and a simulated value the relative error can be calculated from the following formula:

$$\left(\frac{\text{Observed - Simulated}}{\text{Observed}}\right) * 100\% \qquad (2.26)$$

The relative error tells us how close the approximate solution is to the optimal solution

CHAPTER THREE

METHODOLOGY

3.0 Data sources, Collection and Preparation

In this study the following data type were collected from different sources. Geological maps scale of 1:125,000 for Arusha and Shambarai Quarter Degree Sheet number 55 and 71 respectively, were obtained from Madini Dodoma, topographic maps sheets 55/3, 55/4, 71/1 and 71/2 on 1:50,000 scales were obtained from the Ministry of Land and Human Settlement Development, rainfall data in isohyetes form was obtained from the Hydrological year book 1971-1980. Soil and land use data were obtained from the Water Resources Engineering data base whereas Borehole data were obtained from the Ministry of Water and Irrigation, Dar es Salaam and Arusha offices of the Drilling and Dams Construction Agency (DDCA)

3.1 Data Processing

As stated early data obtained in hardcopy format, geological maps and Isohytal for Pangani basin, were converted into soft copy through scanning followed by on screen digitization in order to produce the images which were saved in Tiff format. Digital elevation model (DEM) of 90 x 90 m obtained from the WRE data base was used to produce contours also used to produce thematic layers (These are drainage density, slope steepness and the elevation), later on were used in the GP-model.

Aquifer boundaries delineation was done based on the geological maps with the aid of some interpretation obtained from topographical maps while aquifer categorization and determination of aquifer parameters (Transmissivity and storativity) was done through using borehole pump test data.

3.2 Aquifer Boundaries Delineation

Aquifers can prove to be quite complex, although textbook definitions make them sound to be very neat and discrete. In turn determining the exact boundaries of these different underground strata is extremely complex (Kahimba 2002).

But in groundwater hydraulic the general assumption taken is that groundwater aquifer is horizontal and has infinite area of extent, but in some regions due to changes in geologic properties and subsurface terrain make them not conforming to that assumption. During the field visit in Arusha city the author managed to consult a number Hydrogeologists from Pangani River Basin (Sub-basin office) and DDCA Arusha office. Outcome of consultation revealed that there is no existing aquifer boundary map for the city. Thus, upon coming back to the college the author started working out on how to establish the Arusha aquifer boundary map based on the geological and topographical maps information and for the study area.

3.2.1 Procedures for delineating aquifer boundaries

Since data required were geological and topographical maps, they were to be scanned, followed by digitization in order to produce images.

Studied informations from geological and topographical maps helped in establishing the aquifer boundaries. The information revealed that the area is bounded by four boundaries. These boundaries were based on the geological boundaries, Rivers as the no flow boundaries and in some parts geological structures (fractures) were also incorporated in establishing the aquifer boundaries.

The aquifer in the study area can be divided into two parts according to the geological formations. The Northern aquifer is made up of alluvial deposit to the northwest and mantling ash materials on the northern part. These mantling ash materials are characterized by patches of iron oxides due to weathering. Some are completely obscured with relic textures of parent rocks while others are completely not obscured. The second aquifer runs from middle to south consisting of red brown soil intercalated with lahars of various ages and basalts rocks. The Lahars are porous lavas; however their pore spaces are not necessarily interconnected to suggest good aquifer. Likewise to the far south there are basalt rocks which form the barrier as the base of the formation, unless they are fractured but in general they are not having high groundwater potential.

3.2.2 Data Preparation and Processing

Since the Model uses spatial data (Raster format) as an inputs. It was necessary to convert all those data obtained from hard copy to soft copy format. Thus, geological maps obtained in hard copy format with latitudes and longitudes coordinates were first converted into softcopy. The maps were converted to soft copy images through scanning and the produced images were saved as graphic files (*tiff). Later on the images were added into ArcView window, and extensions from file pull down menu were loaded. These extensions were Tiff 6.0 image support, 3D analyst, spatial tool and spatial analyst.

Upon loading the extensions, two windows were opened and set for image conversion by clicking the transformation pull down window and then set from view was checked for the view 1 and set to view devoted for view 2. “From view” window was made activate and image theme was converted to grid from theme pull down window. Then the newly produced grid theme was activated followed clicking the transformation pull down window and creating a Link table option. Four control points were selected from the active grid of the geological maps. Their Eastings and Northings were recorded and edited into editable link table as from X and from Y respectively. Longitudes and Latitudes (in decimal points) from the grid map corresponding with the Eastings and Northings were recorded as to X and to Y respectively.

In order to transform the coordinates, a link table was set by clicking to the transform pull down menu and the set link table was selected. Finally the warp menu was selected from transformation pull down menu with specification value 1 since there were only four coordinates point then the nearest neighbor was selected.

New view (To view) was activated of which the newly transformed theme was loaded. Then, a new theme was added into the view followed by digitization process of different features such as river for boundaries and lineament features.

The above procedures were repeated for all the images within the aquifer boundaries. Later on, the produced themes in shape files (*shp) were merged together to form a single boundary map. The merging process was made possible by loading the Geo-processing extension. That is, from the file pull down menu window the extension was selected and then the Geo-processing extension was checked. In the main ArcView 3.2a window, the View pull down menu was selected, and the Geo-processing extension was also chosen. Then, all the Shape files to be merged were activate, and finally merged.

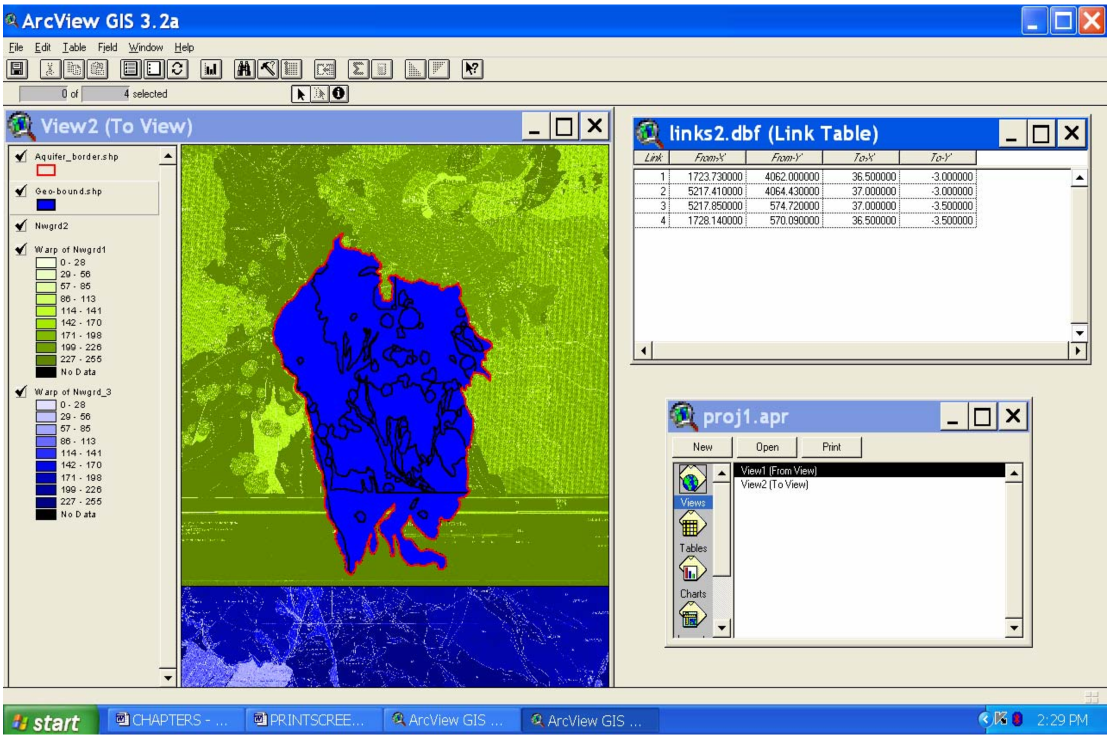


Figure 3.1 Showing digitization ArcView window and tables

Figure 3.1 above displays the transformation procedure done during the digitization process. Geological maps in geographic units were transformed to Universal Transverse Mercator (UTM). It shows a transformed geological map with a digitized aquifer map for Arusha city. Also inside there is a table of coordinates which was linked before warp activity was performed.

3.2.3 Map Projection

Since geological and topographical maps were in different projection, and in the final analysis all produced grid overlay are to be overlaid so as to produce the required groundwater potential map. Because of that all maps which were formally in the latitude-longitudes coordinate system had to be converted into the Universal Transverse Mercator. In this projection all the maps are in SI unit (i.e metres).

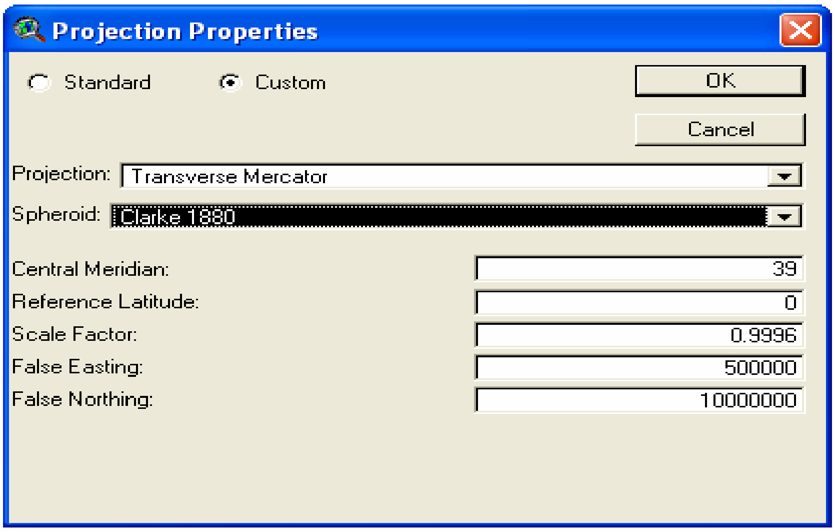


Figure 3.2 Projection Properties window

The above figure displays the Projection Properties dialogue box when setting the map projection. During this exercise the category and zone type were set as UTM-1983 and zone 37 respectively, then custom was checked whereby the projection was set as Transverse Marcator, spheroid was Clarke 1980, central meridian 39, reference Latitude was 0, Scale factor was 0.9996, False Easting was 500000 and the False Northing was 10,000,000. Finally ok button was pressed to set the projection.

3.3 Aquifer Categorization by using Pump Test Data

3.3.1 Introduction

Aquifer categorization process was done by using computer software known as Aquifer Test model. Categorization of an aquifer is a must since the information obtained will be used in the Aquifer characterization process. The results obtained will be used to determine the groundwater potential zones and reserves of the aquifer.

Aquifers are categorized based on existing information, aquifer boundaries range from reasonable assessments (where detailed information is available) to general approximations (scarce information availability).

At a minimum, the test provides an estimate of the aquifer's transmissivity and storage coefficient.

The aquifer test can also provide a useful characterization of the aquifer. When properly conducted and the data appropriately analyzed, information may be obtained on the aquifer conditions (i.e.-confined, leaky-confined, and unconfined).

3.3.2 Categorization of Aquifers

This process was done for the aquifers by using the pumping test data of existing boreholes. The analysis used cumulative time against drawdown for plotting. It was done in Excel software whereby plotting use both the log-log and linear- log scales to produce the curves. The produced time drawdown curves were matched with the standard time-drawdown curve to seek for the correlation.

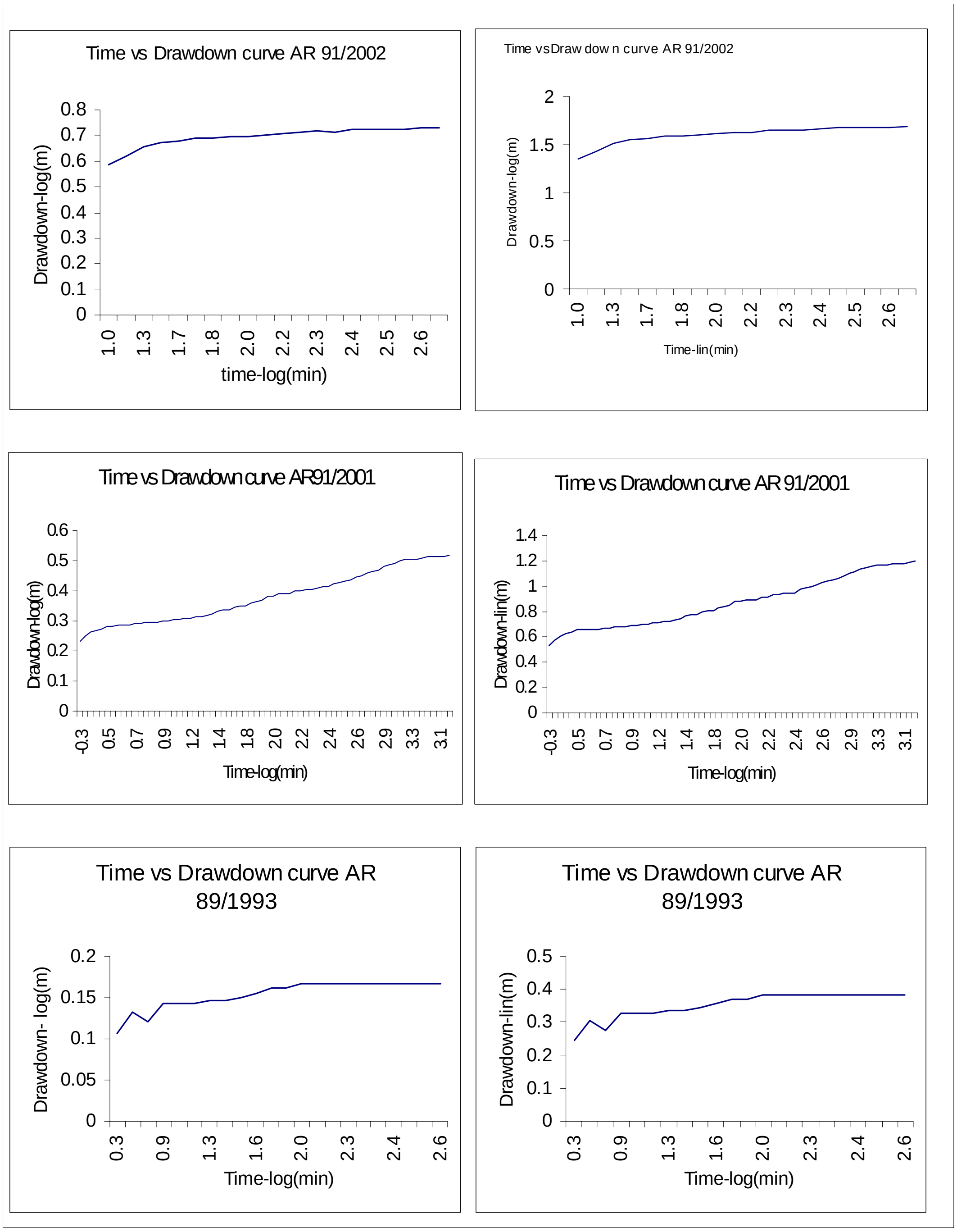


Figure 3.3 Time-drawdown curves for Arusha aquifer (Unconfined aquifer)

3.4 Prediction of Groundwater Potential Zones

3.4.1 Introduction

Determination of Groundwater potential zones for locating boreholes and estimation of aquifer yield in Arusha city were performed by using Groundwater Potential model (GP-Model). The GP- model used hydro-geologic parameters derived from the study area to evaluate groundwater potential zones of aquifers.

3.4.2 Data Acquisition

The main data used for this study were geological and topographical maps which were in hard copy form. These data were obtained from different Government institutions as shown below.

Topographic maps on scale 1:50,000, which were collected from Government Mapping Division, Ministry of Land and Human Settlement were used to obtain surface contours through on -screen digitization of scanned maps using ArcView GIS software. The contours' digital elevation model DEM were used to derive slope and topography elevations.

Geological maps sheets 55 and 71 at 1:250,000 scales collected from IRA and Madini Dodoma respectively. They were used to determine lineament density and lithology. Rainfall data (In Isohyets form) obtained from the Ministry of Water and Irrigation (Hydrological year Book 1971-1980), Land use and Soil maps were collected from WRE database of the UDSM. Drainage densities for the study area were derived from the regional DEM using HEC Geo-HMS extension of the Arc View GIS software.

a.) Annual rainfall (R_f)

Data for Mean Annual rainfall of the study area (MAR) as stated early was obtained from Hydrological year book in hardcopy, so the main task was to scan and digitize the Isohyets in order to get images of these Isohyets. After digitization the following procedures were done.

- The isohyets data in shape file (*shp) was selected. From surface pull down menu, option of create TIN was selected and the data were interpolated to grid. The interpolated grids were again converted to grid using theme pull down menu. The grid coverage was then clipped to boundary map to get rainfall grid theme within the aquifer boundary. The grid theme was then reclassified into seven classes to get annual ranges of equal interval to correspond with standard range and weight as presented by Krishnamurthy, Arul, Jayaraman and Manivel (1996). As a result GP model weights for rainfall were assigned accordingly for use in the final analysis with the model.

Table 3.1 shows reclassified annual rainfall with their corresponding weights as presented by Khairul et al, 1985.

Table3. 1 Annual Rainfalls

Annual rainfall (mm)	Weight
1236 – 1400	20
1071 – 1236	20
907 – 1071	10
743 – 907	10
579 – 743	10

Figure 3.7: Shows the reclassified rainfall grid overlay of the Arusha city aquifer, and it was used for further integration with other parameters in the GP-model.

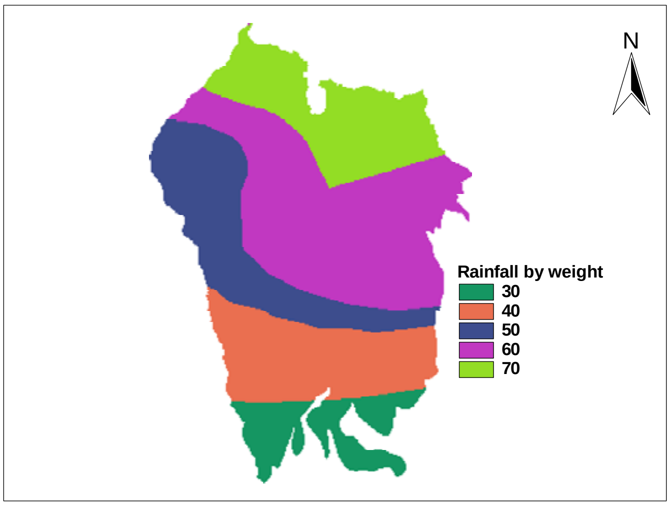


Figure 3.4 Shows rainfall grid overlay

b.) Lithology (L_t)

As stated early the geologic maps in hard copy form were converted to soft copy through scanning and then on-screen digitization process was followed for tracing of sub-regions in order to acquire geological features. The procedures for creating the required lithology overlay in the model were:

- Project window containing lithological features in Latitude-longitude coordinate system was projected into UTM system of units using view - properties pull down menu.
- The lithological features were then merged together using Geo-processing wizard. The attribute table for the resulting shapefile was edited to include polygon name and corresponding weights. The shapefile was converted to grid layout with Lithology weights as value field.

Table 3.2 shows lithological features with their corresponding weights as presented by Khairul *et al.*, 1985.

Table3. 2 Lithology

Lithology	Weight
Alluvium	70
Red soil	40
Alkaline volcanic	30
Mantling ash	20
Basalt	10
Lahars	5

Figure 3.13: Shows Lithology grid overlay for various lithological features from the study area.

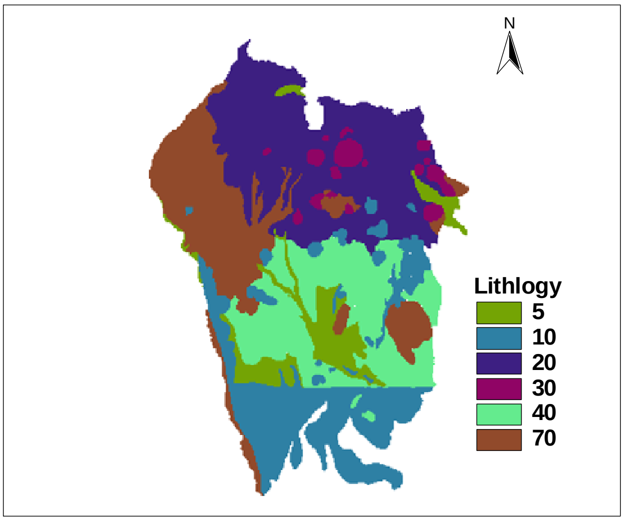


Figure 3.5 Lithology grid overlay

c.) Lineament Density

From geological maps the lineament lengths were measured within the aquifer boundaries. The obtained results were used to calculate lineament density as per the following formula

Lineament Density = fractures (km)/ Basement Area (km^2) (3.1)

The lineament density values together with their weightages were added in attribute table of lineament density project file. Weight field was used to prepare Lineament density grid overlay.

Table3. 3 Lineament Density

Lineament density (km/km2)	Weight
> 0.0075	60
0.0055 – 0.0075	50
0.0035 – 0.0055	40
0.0015 – 0.0035	30
< 0.0035	20

Table 3.4. Shows range of lineament density as derived from topographical map and their weights as presented by Khairul *et al.,* 1985.

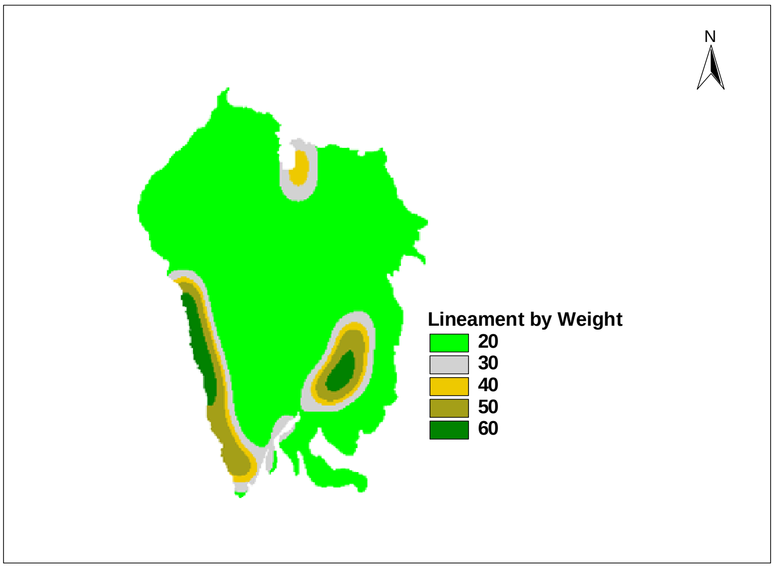


Figure 3.6 Lineament density grid overlay

d.) Land use

Land use overlay was obtained from the Pangani basin data file (from WRE data base). The file was loaded in Arc View window and later on the aquifer boundary shape file which was in grid format followed.

- The loaded land use shape file was converted to grid. From the analysis pull down window the map calculation was selected, and then calculation in order to obtain the land grid overlay was done.
- Attribute table was edited to correspond with land use weights as required in GP-model. Then the land use grid was prepared using land use weights as value fields.

Table 3.5 shows land use data and their corresponding weights which were assigned as per Khairul *et al.*, 2002

Table3. 4 Land use

Land use	Weight
Urban/Cleared land	10
Forest	20
Agriculture	40

Figure 3.10 displays land use grid overlays with the weight score value assigned according to Khairul *et al.*, 2002

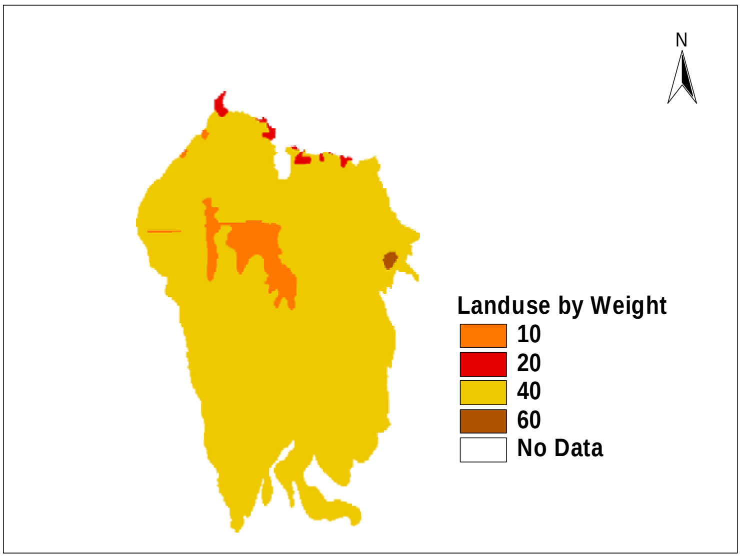


Figure 3.7 Represent weighted Land use grid overlay

e.) Slope steepness

Slope steepness of the study area was obtained from the digital elevation model (DEM). DEM was loaded into ArcView window then the boundary shape file of the study area was also added, followed by Grid analyst extension from the file pull down menu. The procedures were as follows:

- From the surface menu derive slope was selected whereby the slopes of the area was automatically created.
- From the Grid analyst pull down menu, option for extracting grid theme using a polygon was selected as a result the slopes of the area was extracted.
- Then the extracted slopes were reclassified into five classes as per Groundwater potential model requirements.
- From surface pull down menu, derive slope option was selected and slopes in degrees were computed for the DEM. The computed slopes were reclassified into five classes according to GP model slope steepness weights as shown in Table 3.6.
- Reclassified DEM shapefile was again converted to grid with slope steepness weights as value fields. The resulting grid was a slope steepness grid overlay.

Table3. 5 Slope steepness

% Slope	Slope gradient	Slope Zone	Weight
0 – 7	0° - 3°	Almost Flat Topography	50
8 – 20	10° -9°	Undulating Rolling Hilly	40
21 – 55	10° - 24°	Hilly Steeply Deserted	30
56 – 140	25° - 63°	Steeply Deserted Mountainous	20
> 140	> 63°	Mountainous	10

Figure 3.11 displays grid overlay for the slope steepness derived from surface contours of the study

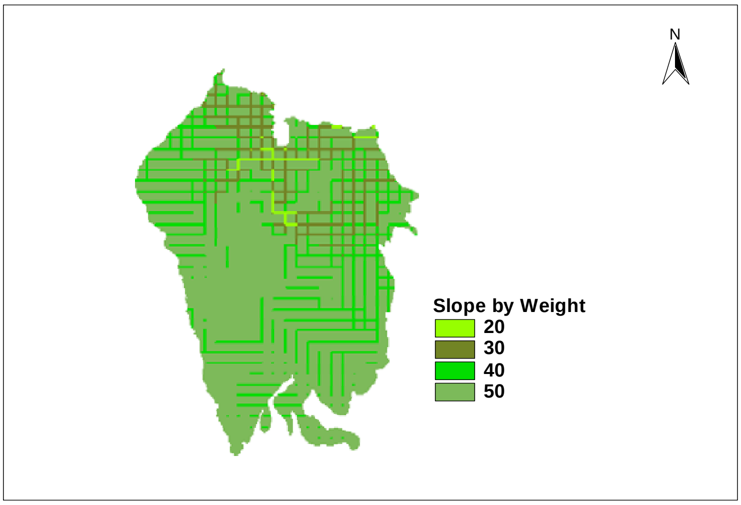


Figure 3.8 Slope Steepness grid overlay

f.) Topography Elevation

This involved classification of topography elevation zones from a datum. The datum elevation contour taken was the lowest contour elevation (900 m a.m.s.l.). Analysis performed from contour DEM grid was similar to slope steepness. Attribute of the reclassified shapefile was edited to include topography weights and Elevation zones. Results are shown in Table 3.7 and Figure 3.12.

Table3. 6 Topography Elevation

Elevation (m)	Elevation Zone	Weight
< 20	Almost Flat Topography	50
20-100	Undulating Rolling Hilly	40
100 – 500	Hilly Steeply Disserted	35
500 – 1000	Steeply Disserted Mountainous	25
> 1000	Mountainous	10

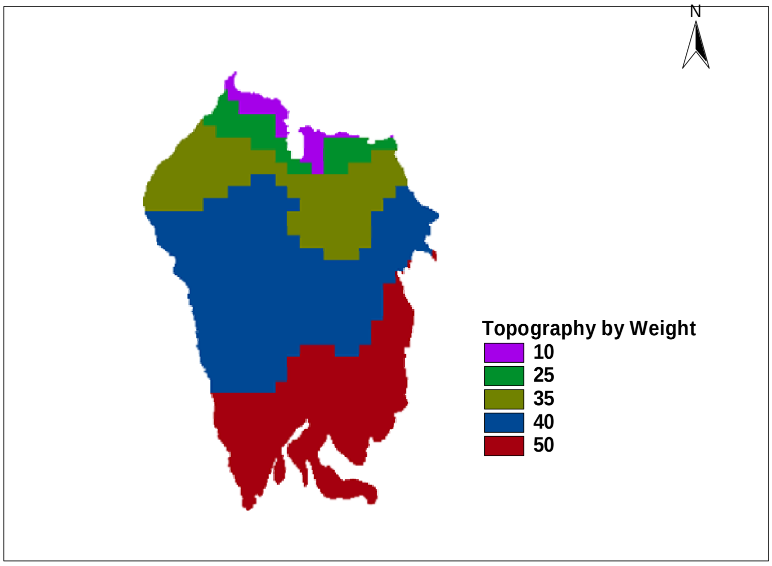


Figure 3.9 Topography Elevation grid overlay

h.) Soil Type

Soil type data file collected from WREP database was loaded in Arc View window. The procedures followed for obtaining the soil type grid overlay were as follows:

- Soil type shape file was loaded into ArcView window then the Arusha city aquifer boundary map was also loaded. Then the Geo-processing extension was loaded and the soil type was clipped from the main soil type.

Table3. 7 Soil Type

Soil type	Weight
Clay	10
Sandy clay	30

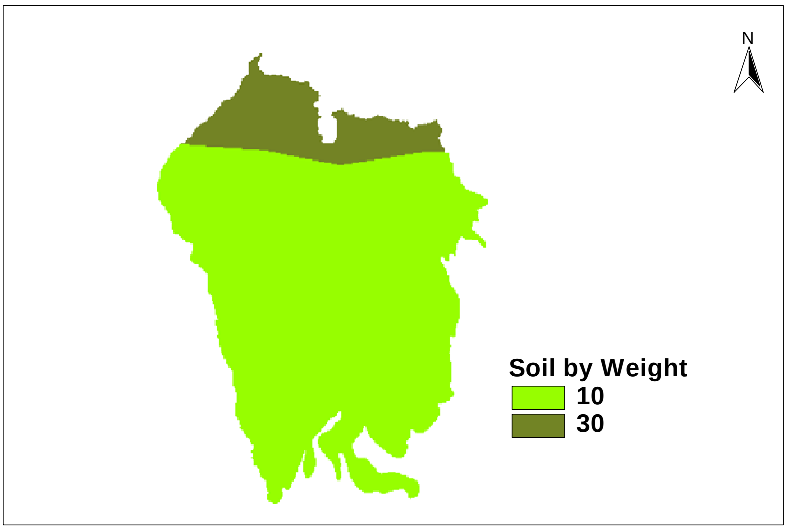


Figure 3.10 Soil type grid overlay

i.) Drainage Density

For determination of drainage density the HEC Geo-FIMS extension was loaded in ArcView project window followed by DEM of the study area.

The following procedures were executed in order to determine drainage density of the study area. In the main view window the DEM of the area was added, then Terrain processing pull down menu was selected thereafter catchment delineation processes were done. Later on the attribute tables for River length and watershed shape files were linked together by using the common identity (ID) column. Aim of doing that was that of having area and length values in the watershed table. Then the drainage density was calculated from the watershed table using the formula below:

$$\text{Drainage density} = \text{River length (km)/ Area (km}^2\text{)} \quad (3.2)$$

The sub catchments shape file was converted to grid using the obtained drainage density values, then the grid was reclassified and weights were assigned to each corresponding class. Converting the reclassified file to grid with weights as value fields finally made drainage density grid overlay.

Table3. 8 Drainage Density

Drainage Density (km/km^2)	Weight
> 0.0055	10
0.0040 – 0.0055	20
0.0025 – 0.0040	30
0.0010 – 0.0025	40

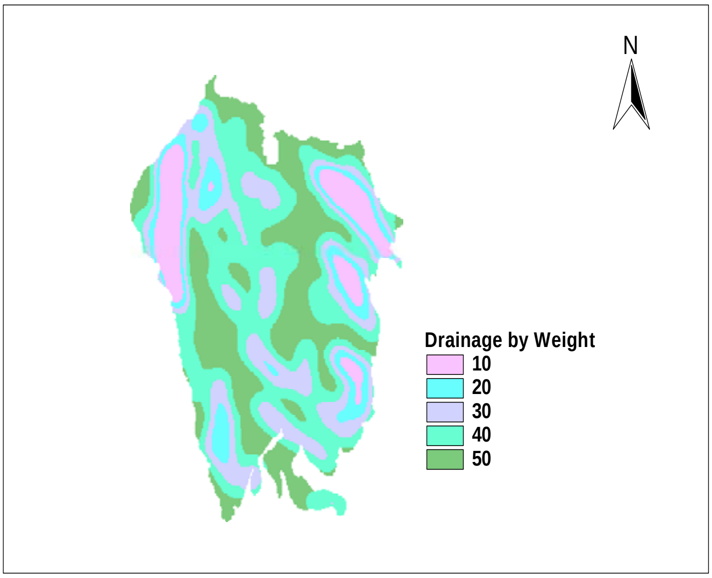


Figure 3.11 Drainage Density grid overlay

Figure 3.18 shows reclassified drainage density overlay of the Arusha city aquifer. The area with weight values 10 and 20 represents areas with drainage density greater than 0.0055 and 0.0040 to 0.0055, according to Edet et al., 1994 areas with high drainage density are usually underlain by rocks of low permeability/transmissivity while area with drainage density between 30 to 40 values represents areas with low drainage density hence underlain by rocks of high permeability.

3.4.3 Integration of data from hydro-geologic grid overlays

At this stage all layers were combined by using the Groundwater Potential model formula (Equation 2.24).

In ArcView, a new window was opened and the grid overlays of the eight parameters produced previously with their respectively weights were loaded.

Map Calculator option from the analysis pulls down menu was loaded and the grids were overlaid together by adding them. Then, the output grid was reclassified into five classes based on the Equal Interval Classification Method, ESRI, 1996 (see Table 3.10).

Finally the reclassified coverage was later converted to grid using estimates of discharge rates to get groundwater potential zones grid overlay. Since the analysis was performed in raster form using GIS, the overlays gave zones that are potential for locating boreholes. Groundwater potential zones were classified as very high, high, moderate, low, and very low. GP - model result is compared to yield of the aquifer. Results of GP - Model are displayed in Table 3.10 and Figures 3.15 and 3.16.

Table 3.9 Final score values of area polygons in Groundwater potential map (Khairul *et al.,* 2000)

Table3. 9 Final score values of area polygons in Groundwater Potential map

Score value	Class of Groundwater zone	Discharge rate(m^3/hour/well)
> 285	Very High	> 22
265 – 280	High	18 - 22
245 – 260	Moderate	14 - 18
230 - 240	Low	10 - 14
< 225	Very low	< 10

The table ascertains that various regions have different groundwater potential. The area having a score above 285 and between 265 and 280 have a very high to high groundwater potential hence represent zones of high discharge rate which is good for groundwater exploration, while area with a score value between 245 and 260 represents zone of moderate groundwater potential with 14 to 18 discharge rate range whereas areas having a score between 230 to 240 and below 225 have low to very low groundwater potential hence represent zones of discharge rate between 14 - 10 and less than $10m^3$/hr/well (Figure 3.16)

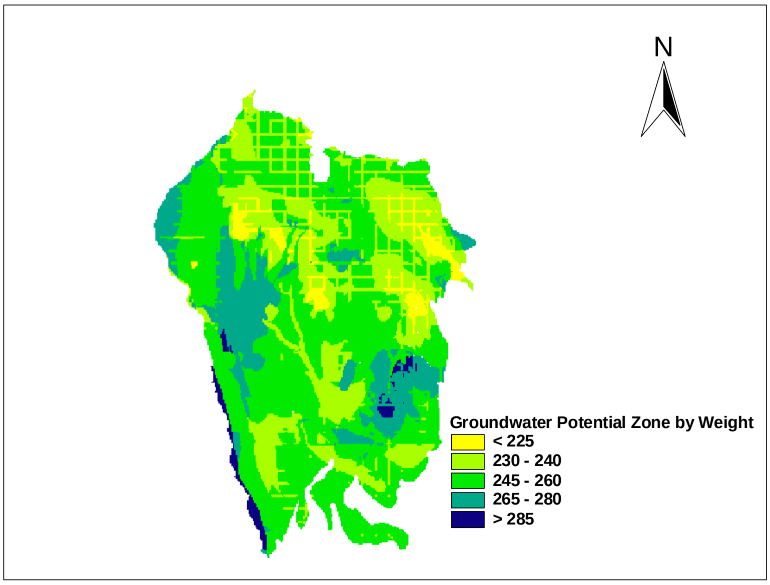


Figure 3.12 Map of Groundwater Potential zones for Arusha city Aquifer

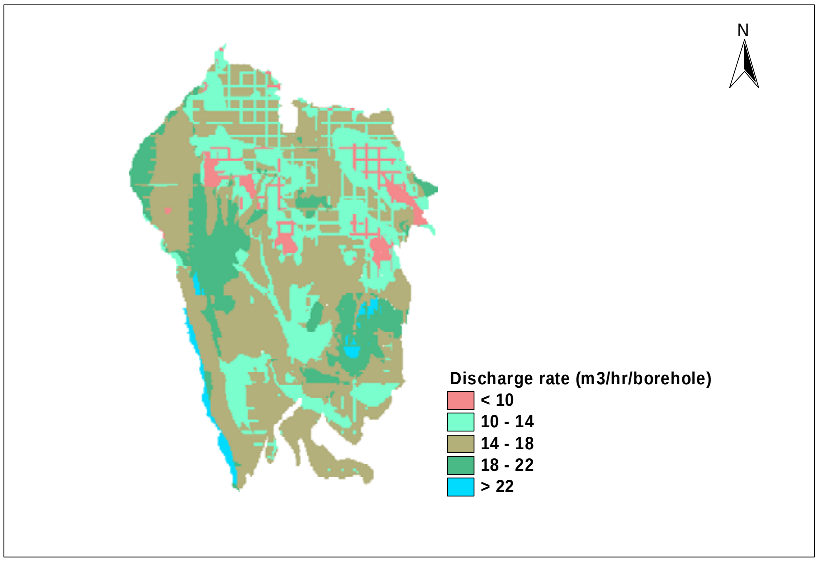


Figure 3.13 Map of Discharge rate Arusha city Aquifer

Figure 3.16 shows the estimated discharge rate for the Arusha city. The zones with high discharge rate are located within these areas having high lineament density and in the alluvial plan.

3.5 Estimation of Aquifer Reserves

3.5.1 General Introduction

One among the objectives of groundwater resources management is to find out the maximum rate that can be can pumped from an aquifer without affecting the hydrologic equilibrium of a particular aquifer.

For protecting an aquifer from exploitation the maximum amount of abstraction (aquifer yield) should not exceed the net annual replenishment into the aquifer. Otherwise excessive pumping will lead to aquifer 'overdraft'. Over abstraction might lead to land subsidence, lowering of water table and salt water intrusion for e.g. sea.

The maximum amount of abstraction (aquifer yield) should not exceed the net annual replenishment into the aquifer.

In order to analyze the total groundwater reserves and replenishment of the Arusha city different information were gathered concerning with the basement topography, aquifer parameters, geometry and categories and the recharge mechanisms. The main data used for analysis were aquifer boundary map which was produced through boundary delineation, transmisivities and storativity parameters obtained from aquifer test model (analysis of pumping tests data), and aquifer thickness obtained by analyzing lithological logs and strike layers.

The results obtained from estimation of aquifer reserve are very useful for proper planning development and utilization of groundwater resource in Arusha city.

3.5.2 Groundwater Reserves Estimation using Aquifer Porosity Method

Total aquifer reserve includes the dynamic reserve and static reserve. The aquifer porosity method was used in this study for estimation of total groundwater reserve.

The total aquifer reserve through this method is given by multiplying the total volume of aquifer material with the aquifer porosity.

$$Q = A \times h \times \eta \qquad (3.3)$$

Where: A x h = total volume of saturated material

η = aquifer porosity.

The following procedures were done for estimating groundwater reserves

a.) **Data analysis**

Aquifer layers – Establishment of aquifer layers were carried out by using groundwater strike layers from the pumping test and lithological logs together with the surface contours derived from the DEM. Different layers of aquifer were established as shown in appendix Cs. The tabulated aquifer layers were saved as the text delimited file (*txt) which later on were loaded into ArcView window as text file. In arcView window the depth to each layer was subtracted from the surface elevation grid overlay to get corresponding strike elevation grid overlays. Obtained Layers for the Arusha city aquifer are: First strike elevation, first strike end elevation, second strike elevation, second strike end elevation, third strike elevation and basement elevation.

Aquifer porosity

Using lithological logs obtained from few boreholes data available, materials for each layer were classified. The corresponding aquifer porosities were tabulated by comparing with table of porosity ranges for materials (Freeze, 1979 and Todd, 1980). Table 3.10 shows range of values for porosity of various rock materials as presented by Freeze, 1979.

Table3. 10 Range of values of Porosity (Source: Freeze, 1979)

Rock Type	Porosity, n (%)
Unconsolidated deposit	
Gravel	25 - 40
Sand	25 - 50
Silt	35 - 50
Clay	40 - 70
Rocks	
Fractured	5 - 50
Karst limestone	5 - 50
Sandstone	5 - 30
Limestone, dolomite	0 - 20
Shale	0 - 10
Fractured crystalline rock	0 - 10
Dense crystalline rock	1 - 5

Table3. 11 Shows Aquifer porosity for different strike layers.

ID	Source	XPR	YPR	Layer 1	Layer 2	Layer 3	Layer 4	Average
1	AR 05/04	245524	9624080	0.35				0.35
2	AR 225/04	245782	9622160	0.375	0.375			0.375
3	AR 690/06	240730	9630237	0.375	0.375	0.463		0.404
4	AR 445/05	241730	9627726	0.375	0.3	0.35	0.381	0.352

Porosity grid overlays of each aquifer layer were prepared by using ArcView GIS as shown in figure 3.16 below.

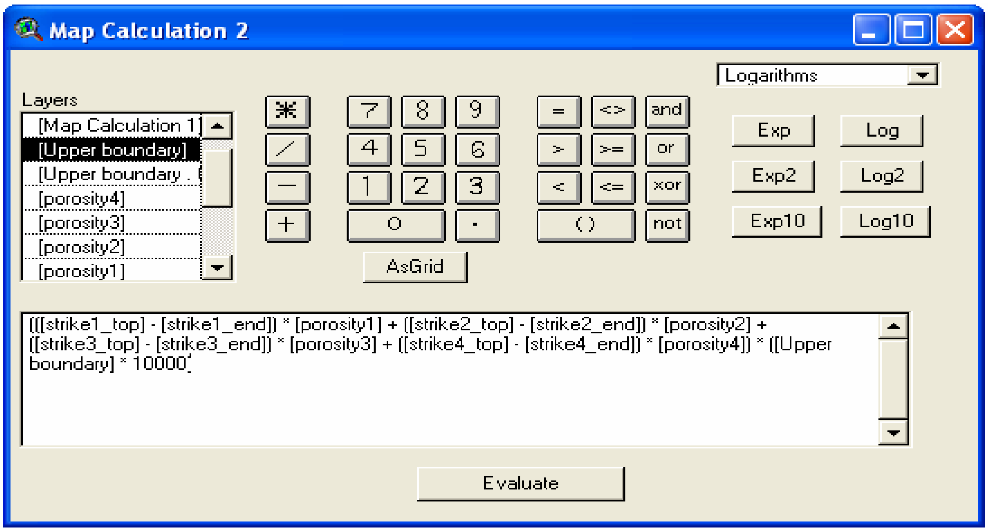


Figure 3.16 Map calculation for grid overlays.

Figure 3.16 above shows how the volume of each aquifer was obtained from a map calculation option. The end strike grid layer was subtracted from the top strike grid overlay and the result was multiplied by the porosity grid overlay of that aquifer to get the volume. This was done for all aquifers and finally the volumes were added up and multiplied by boundary area and the pixel size (100*100).

b.) Estimation of Aquifer volumes and total Groundwater Reserves

For calculation of the aquifer volume, aquifer strike layers and porosity grid overlays were opened on a new ArcView project window. By using a map calculator from analysis pulls down menu an aquifer volume (obtained by subtracting strike end elevation from corresponding strike elevation) was the screen shot Figure 3.17.

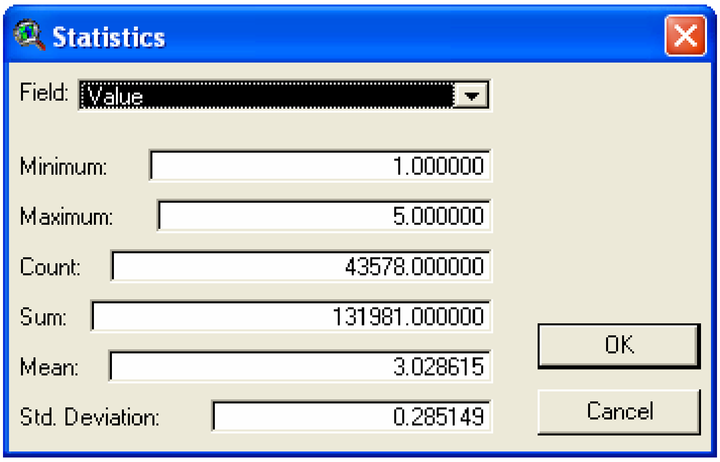


Figure 3.17 Statistic calculations for grid overlays

The value obtained from map calculation was total volume of aquifer (m^3/hr/pixel), thus the total volume of the entire aquifer acquired by using a map statistic option is

=Total Sum for the aquifer(m^3/hr)x24 hours/day x365 days/year x10^{-6} (3.4)

= 1,156.15 x 10^{-6} m^3.

Table3. 12 Total available groundwater reserves from aquifer porosity method

Aquifer type	**Area (km2)**	**Volume (Million m^3/year)**
Unconfined	458	1,156.15

3.5.3 Estimation of groundwater yield from Groundwater Potential-model

The results obtained from the groundwater potential model (figure 3.15) were used for estimating the aquifer yield. In the ArcView window the groundwater potential theme (m^3/hr/borehole) was double clicked in order to calculate the statistics values. The corresponding values obtained from the statistics are shown in Figure 3.18 below:

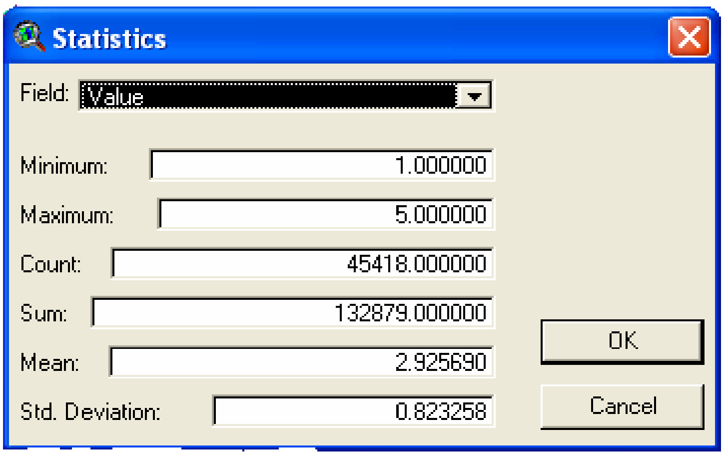


Figure 3.18 Groundwater Potential model statistic results

From the above figure results show that the estimated average discharge is 2.926m^3/hour/borehole. Thus, the total annual discharge from the aquifer is calculated as

Q (m^3/year) =total sum for the aquifer x 24 hours/day x 365 days/year (3.5)

$$Q = 132879 * 24 * 365 * 10^{-6}$$

Therefore total annual yield for the entire aquifer is **1164.02*10^6**m^3/year.

Comparison with Groundwater yield from boreholes data:

The groundwater yield data from appendix (Table D-l-) were plotted using Arc View GIS window. Similar procedures for preparing grid overlay maps were followed from the boreholes yield text file. The results of boreholes grid overlay are presented in figure 3.23 below whereas the results obtained from the map statistics (figure 3.22) is given as:

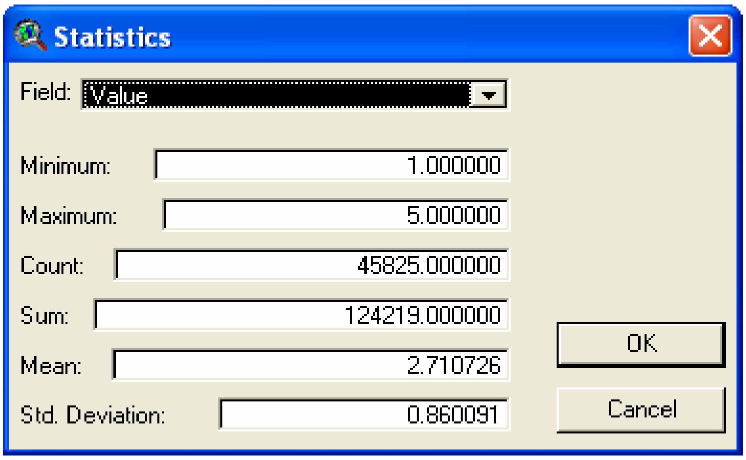


Figure 3.19 Groundwater yield results

Average borehole yield obtained from the above groundwater yield statistics is 2.710726 m^3/hour/well.

Annual yield of the aquifer is given as

$$Q\ (m^3/year) = (m^3/hr/aquifer\ area) \times 365 \times 24 \quad (3.6)$$

$$Q = 124219 * 24 * 365 * 10^{-6}$$

Therefore the total estimated annual yield from boreholes is $\mathbf{1088.16*10^6}$ m^3/year.

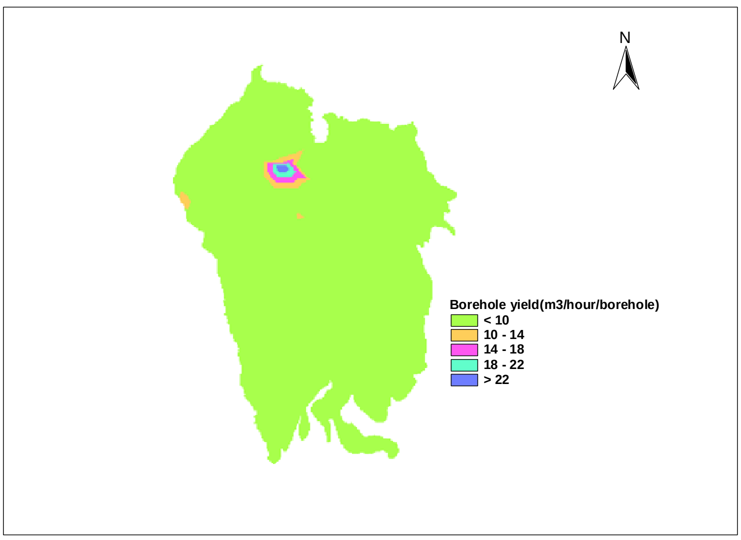


Figure 3.20 Boreholes Yield grid overlays for the study area

CHAPTER FOUR

RESULTS AND DISCUSSION

4.0 Introduction

This chapter covers the results and discussion. The results discussed here were obtained through the methodology described in chapter three above. Analysis was based on geological and topographical maps, isohyets and DEM. In the analysis ArcView GIS 3.2 software was used. Aquifer characterization and mapping was done on Groundwater Potential model was used to estimate the groundwater potential map zones whereas aquifer porosity method was used for estimating the available groundwater reserves. The discussion in this chapter is based on the results obtained from the analysis.

4.1 Aquifer Boundaries Delineation

The results obtained from the Aquifer boundary delineation process is a map shown in figure 4.1 below. The map is in the shape file which was obtained through on screen digitization and interpretations of geological and topographical maps. The Eastern boundary runs approximately along River Nduruma which follows the Lahar geological formation in the eastern side of the study area while in the North the Aquifer is bounded by slope of Mt. Meru just as it start to flatten whereas the southern boundary was a geological boundary between the basalt and red soil derived from volcanic rocks. In the western the aquifer bounded by River Engare Olmotonyi which runs along the fractures.

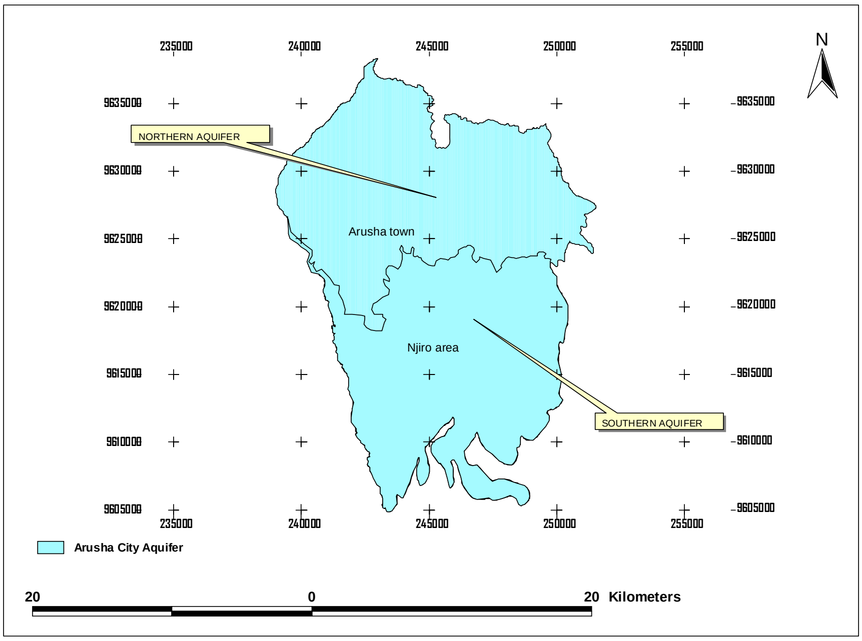


Fig 4.1 Aquifer boundaries for Arusha city

The aquifer in the study area is mainly composed of alluvial deposit to the northwest and mantling ash materials on the northern part. These mantling ash materials are characterized by patches of iron oxides due to weathering. Some are completely obscured with relic textures of parent rocks while others are completely not obscured. The aquifer receives its groundwater flows from the foot of Mt. Meru hence there is a great possibility of having a good reservoirs as very high yielding wells exist in the area.

On the southern part the aquifer consisting of red brown soil material intercalated with lahars of various ages and basalt rocks. The lahars are porous lavas; however their pore spaces are not necessarily interconnected to suggest good aquifer that is why in this area where there is red brown soil the groundwater potentiality is little. Likewise to the far south there are basalt rocks which form the barrier as the base of the formation, unless they are fractured but in general they are not having high groundwater potential.

4.2 Groundwater Potential Zone Map

The groundwater potential map of Arusha city aquifer is shown in the figure 4.2 below. A map produced by using a Geographical Information System (GIS) model, through integration of prepared thematic maps including annual rainfall, lithology (geology), lineament density, land use, topography, slope, drainage density and soil type. The map classifies groundwater potential zones as very high with discharge rate > 22 m^3/hr/borehole and very low <10 m^3/hr/borehole.

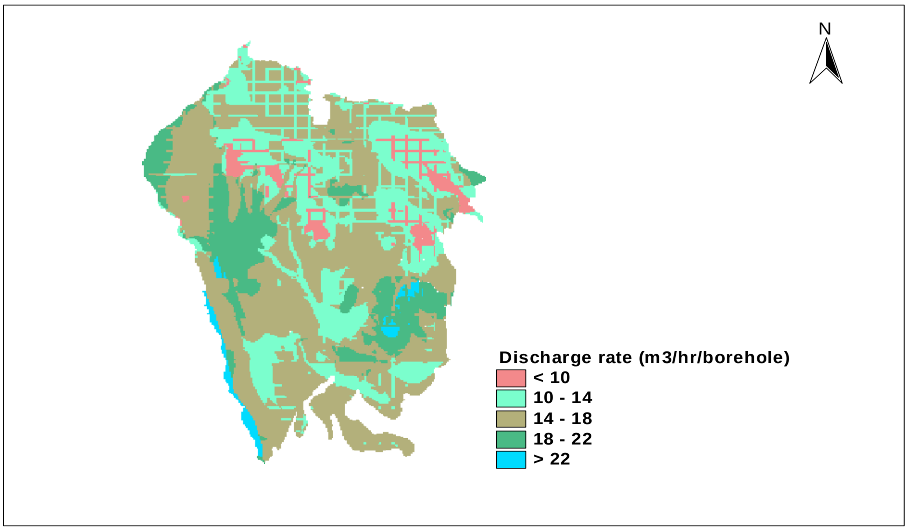


Fig. 4.2 Map of Groundwater Potential zones for Arusha city Aquifer

Table 3.12 shows contributions of each hydro-geologic feature to groundwater potential. Form the table it is observed that zones of very high to high groundwater potentials are found in agricultural areas located in almost flat to undulating rolling hilly with elevation <20 and between 20 to 100 underlying alluvium and red soils. These zones have low to moderate drainage density but have low to moderate annual rainfall and clay soil. For the high groundwater potential zone found in the alluvium plain there is absence of lineament density but for the one in the red soil area is favored by the presence of a lineament density.

Zones of very low groundwater potential are found in forest, urban and Cleared land areas located in almost flat topography areas with elevation less <20m and between 20 and 100m which is underlain by lahars/red soil. This zone has low to moderate drainage density, low to moderate lineament density.

Table 4. 1 Summary of hydro-geologic contributions

Layer\ Potential zone	Very High	High	Moderate	Low	Very Low
Land use	Agriculture	Forest/ Agriculture	Forest/ Agriculture	Agriculture	Forest/urban/ Cleared land
Rainfall(mm)	1236-1400 1072-1236 907-1072	1236-1400 1072-1236 907-1072	1072-1236 907-1072	907-1072	907-1072
Lithology	Alluvium	Alluvium/ Mantling	Volcanics	Basalts/ Volcanic	Lahars/ Red soil
Topography Elevation (m)	<20 /20-100	<20 20-100 500 - 1000	100 - 500	100 – 500/ 20 – 100 / 500 - 1000	20 - 100
Lineament Density (km/km2)	High	High	High	High	High
Slope (%)	0 - 7	0 - 7	0 – 7/8 - 20	8 – 20/ 21 - 55	56 - 140
Drainage Density (km/km2)	High	High	High	High	Low/ Moderate
Soil Type	Clay	Sand clay	Sand clay		Clay/ Sand clay

Summary of results in Table 3.12 indicate different polygon categories of each of the thematic layers and their relevance to groundwater potential. Alluvial plains and mantling ash areas have very high potential of groundwater. Also volcanic areas occurring on gently slopes and moderate drainage density areas have high potential. Areas with basalt material and steeply mountainous ones have low potential to groundwater. Groundwater potential is also moderately high on higher plains receiving high rainfall and having moderately low drainage density.

4.3 Estimation of Available Groundwater Aquifer Reserve

From calculation the total available groundwater reserves of Arusha city is estimated as 1156.15 Million m^3/year obtained from the aquifer porosity method while estimation of groundwater yield from Groundwater Potential model (figure 4.19) and from borehole yield (figure 4.20) are 1164.02 and 1088.16 Million m^3/year respectively.

The values indicate that the aquifer has a large groundwater potential that is still unexploited. Hence groundwater can still be used as an alternative source without affecting the natural groundwater balance.

However, proper extraction policy has to be imposed to ensure proper distribution of well fields to avoid excessive lowering of water levels in the wells below pumping intakes.

Relative error Calculation

From this study the relative error value is given below as per equation 3.25

$$RE = \left(\frac{1088.16 - 1164.02}{1088.16}\right) * 100\% = 6.97\%$$

Whereas those from previous study done by Kahimba 2002 in Kilimanjaro municipality is calculated as

$$RE = \left(\frac{18911.05 - 19536.04}{18911.05}\right) * 100\% = 3.3\%$$

The Relative error values obtained from these two studies revealed that they are less than 20% hence the observed result from borehole yield and simulated (found) result from Groundwater potential model are comparable.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.0 Conclusions

In this study the aims were to assess groundwater potential zones and estimate the groundwater reserves for Arusha city. Mapping of groundwater potential zones were done through Groundwater Potential model under ArcView GIS environment while estimation of the total available groundwater reserves for the aquifer was calculated by using aquifer porosity method.

From the aquifer characterization process it was observed the city aquifer is unconfined aquifer which comprises of mantling ash and alluvium as the base aquifer in the northern part whereas in the southern part is covered by red brown soil (weathered basalt) and the basalt rock.

Results obtained from Groundwater reserve suggest that the area has very high groundwater potential. Further it was revealed that the estimated yield of aquifer from boreholes is comparable with yield as estimated by using GP model.

Likewise the Groundwater potential model suggests that hydrogeologic settings (rainfall distribution, drainage features, elevations, lithology, vegetation cover, soil types and geological structures) are very good indicators of occurrences of groundwater for a given area.

Alluvial plains and mantling ash covered areas have very high potential of groundwater as proved by the presence of 15 boreholes in the mantling ash areas which are used by Arusha Urban water supply and Sewerage Authority (AUWSA).

Also volcanic areas occurring on gently slopes and moderately drainage density have high potential. Areas in the southern part with basalt material have low potential groundwater. Groundwater potential is also moderately high on higher plains receiving high rainfall and having moderately low drainage density.

Observations made from collected boreholes data from the city showed that groundwater in the northern aquifer occurs in layers at shallow and deep levels in the aquifer. The average first strike in this area is 40 m below ground level while the common drilled depth is 50 - 200 m and the yield is ranging from 8–145 m^3/hr.

For the southern aquifer, the average strike depth is 4 - 27 m and the drilled depth revealed from boreholes number AR 05/2004 and AR 225/2004 is about 105m below ground level and the yield is $9m^3$/hr.

5.1 Recommendations

Since the contribution of groundwater resource for Arusha city is very large compared to the surface water, its exploitation and abstraction from the present wellfield and those from private borehole should be managed in a sustainable manner. Likewise there is a need to have more development on groundwater resources management and monitoring activities so that water allocation for different water users such as industrial and agricultural ones rely on the groundwater leaving the surface water for domestic users. The Pangani Basin Water Office should also have a database for monitoring groundwater resources.

Groundwater potential model supported by GIS techniques is a very suitable method for predicting groundwater potential zones.

A map produced using GP model can be used as basic information for locating boreholes since apart from showing groundwater potential zones it also predicts the expected yield from borehole located on the respective groundwater potential zone. The observed results of this study should not be taken as final ones, thus actual field records must be done as the distribution of collected data was not fully covering the entire aquifers of study area.

Suggestions for further studies on availability of groundwater resources should be done by using geophysical methods like vertical electric sound and magnetometer to mention a few. These methods are required to ascertain the groundwater potential zones in order to have a wider coverage of data particularly in those areas where this study could not managed to have data like in the southern part of the aquifer. Also extraction policy to be imposed to ensure proper distribution in the well fields to avoid excessive lowering of water levels in the wells below pumping intakes.

REFERENCES

Anna J and Håkan N (2003). *Water Quality Assessment in the Arusha Wellfield and surrounding:* A Minor Field study in Tanzania: Department of Geology, Chalmers University of Technology, Göteborg, Sweden.

Akpofure, E.Taigbenu, Ron Chaoka, Brian K. Rawlins, Richard Owen and Simon Mkhandi., (2002). "Introduction to Hydrogeology. Ground Module", *Lecture Notes for M.Sc.* (IWRM), University of Dar es Salaam – Tanzania.

Aller, L., Bennett, T. Lehr, H. J. and Petty, R. J. (1985). *DRASTIC: A Standard System for Evaluating Groundwater Pollution Potential Using Hydrogeologic Settings.* EPA/600/2- 85/018, R. S. Kerr Environmental Research Laboratory, U. S. Environmental Protection Agency, Ada, Oklahoma.

Chow, Ven Te (1988). *Applied Hydrology.* McGraw-Hill International Editions.

Chow, Ven Te (1964) *Hand book of Applied Hydrology*. A Compendium of Water Resources Technology. McGraw-Hill International Editions.

Eriksson, E., Gustafsson, Y., and Nilsson, K(1968). "Groundwater Problems", *Wener-Gren Centre International Symposium* Volume III. Pergamon Press Ltd.

ESRI. (1996). *ArcView GIS, The Geographic Information System for everyone.* USA Environmental systems Research Institute.

Freeze, R. A and Cherry, J. A (1979).*Groundwater.* Prentice Hall, Inc. Englewood Cliffs, New Jersey 07632.

Gupta, R.P (1991) *Remote sensing Geology.* New York: Springer- Verlag Heidelburg

JBG Consulting Engineers and GKW Consult (1987).Arusha water Supply Drilling Programme *Interim Report*. Dar-es-salaam.

Johansson, A. and Nilsson, H. (2003).*Water Quality Assessment in Arusha Wellfield and Surroundings*. (Examensarbete med MFS-bidrag) Unpuplished.

Kahimba, F.C (2002). Assessment of *Groundwater Reserves in Moshi municipality Aquifer using GIS.* Unpublished M.Sc. (WRE) Thesis, University of Dar es Salaam.

Khairul, A. M., Juhari, M. A., and Ibrahim, A. (2000). *Groundwater Prediction Potential Zone in Langat Basin using the Integration of Remote Sensing and GI,*http://www.gisdevelopment.net/aars/acrs/2000/ps3/ps31 S.html retrieved on Monday, 3rd March, 2008

Krishnamurthy, J., Arul, M. M., Jayaraman, V., and Manivel, M. (1996) "An Approach to demarcate groundwater potential zones through remote sensing and a geographical information system," *International Journal of Remote Sensing*

Kruseman, G. P., and de Ridder, N. A (1994). *Analysis and Evaluation of Pumping Tests Data. Second Edition.* ILRI, The Netherlands.

Kumar, Ashok, Tomar, Savita, and Prasad, L. B (2002). *Analysis of Hydro geophysical Properties of Aquifer and Reserve Estimation for Sustainable Development of Groundwater in Kewta watershed, Hazaribagh.* Remote Sensing Application Centre, IGSC- Planetarium, Patna - 800001, India.

MacDonald, A, Davies, J, Calow.R and Chilton J (2005), *Developing Groundwater. A Guide for Rural Water Supply,* Bourton Hall, Bourton-on-Dunsmore, Warwickshire CV23 9QZ, UK

Newman, P. and Romberg, P (1992),*Changes in Land Utilization within the Last Three Decades in the Babati Area*, Swedish University of Agricultural Sciences, Uppsala, Sweden, Working Paper 198.

Rao T, B V. M., and Chaundary, B. S (2000). *Integrated Groundwater Resources Mapping in Gurgaon District, (Haryana) India* http://www.Risdevelopment.net/aars/acrs/2000/ts2/water0002.shtml retrieved on Monday, 29th May, 2008

Sandstrom, K (1995).The Recent Lake Babati Floods in Semi-Arid Tanzania- A response to changes in Land Cover? Geografisca Annaler.77A (1-2):pp35-44. (Scandinavian University Press on License from the Swedish Society for Anthropology and Geography).

Sener, E., Davraz, A.and Ozcelik, M (2004) "An integration of GIS and remote sensing in Groundwater Investigation," *Journal of Hydrogeology*

Solomon, S and Quiel, F (2005) "Groundwater study using remote sensing and geographic formation systems (GIS) in the Central Highlands of Eritrea," *Journal of Hydrogeology*

Subramanya, K (1994). *Engineering Hydrology.* Tata McGraw-Hill Publishing Company Limited, New Delhi.

United Republic of Tanzania(1980), *Hydrological year Book* (1971-1980).Pg 84.

United Republic of Tanzania, Arusha Region Water Master Plan, (2000).*Groundwater Resources* (Hydrogeology). Part 111 of the Plan: Methods, Data, Analysis and Assessments. Vol. 14. Final Report.

Tarbuck, E.J and Lutgens, F.K (2002) Earth (2.ed) *Upper Saddle River*: Prentice-Hall, inc ISBN 0-13-092025-8

Todd, D.K (1980). *Groundwater Hydrology, Second Edition.* John Wiley & Sons, Inc. New York.

Todd, D.K.and Mays, L.W (2005), *Groundwater Hydrology, Third Edition.* John Wiley & Sons, Inc. New York.

Yafang, SU (2002). *Introduction to ArcView GIS 3.x.* UCLA Academic Technology Services, http://www.ats.ucla.edu/classes/gis/avchptl.html Thursday, 28th, February, 2008

Volcano World, (2005). Website of the University of North Dakota, http://www.volcano.und.nodak/edu/vw.html Thursday, 28th, February, 2008

APPENDICES

Appendix A-l: Representative Values of Permeability Coefficients

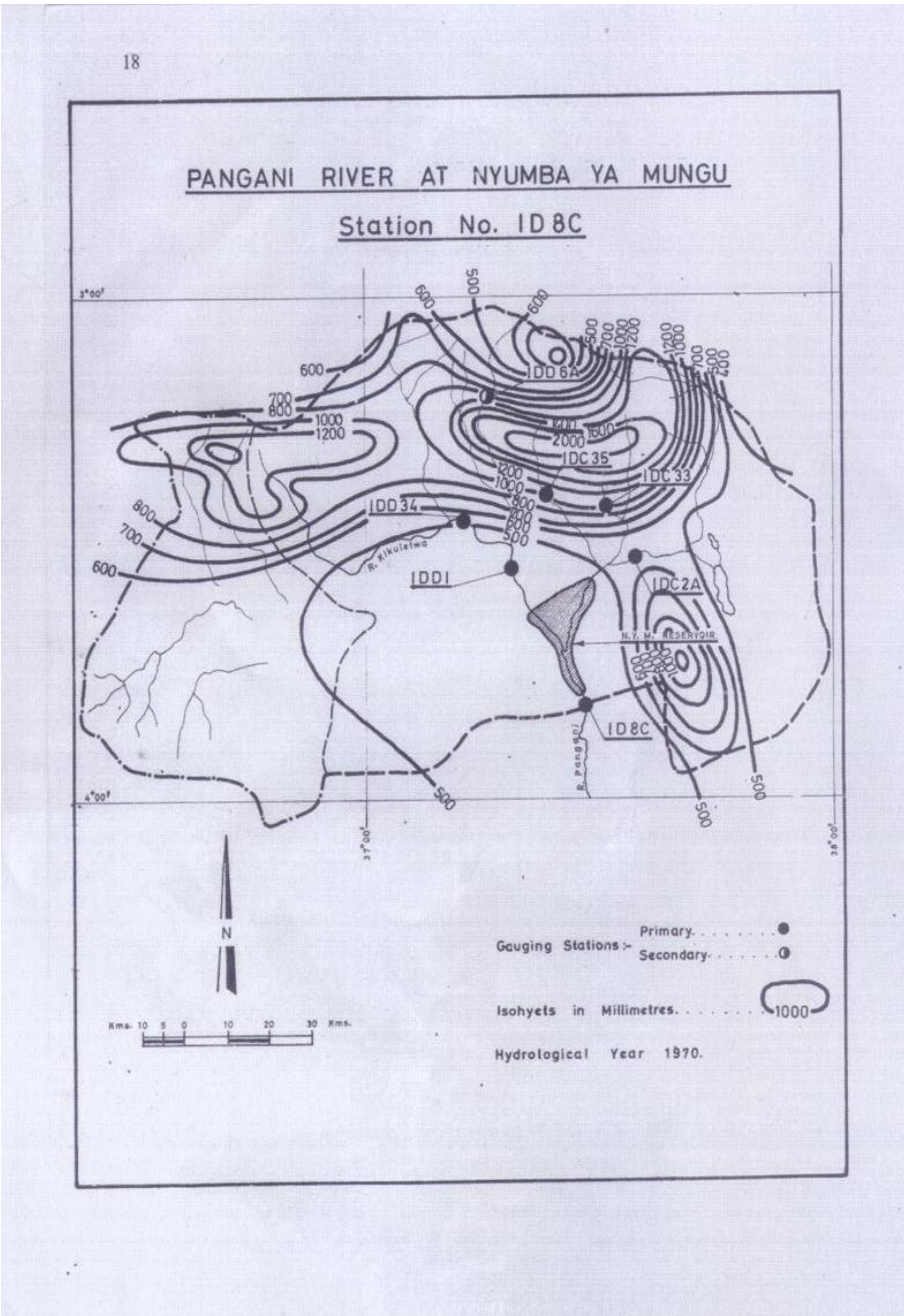
No	Materials	*K(cm/s)*	*K* (m/min)	K_0 (Darcy's)
A.	***Granular material***			
1	Clean gravel	1 -100	0.6 - 60	10^3 - 10^5
2	Clean coarse sand	0.010-1.00	0.006 - 0.6	10 -10^3
3	Mixed sand	0.005 - 0.01	0.003 - 0.006	5-10
4	Fine sand	0.001 - 0.005	0.0006 - 0.003	1-50
5	Silty sand	$1x10^{-4}$-2x 10^{-3}	$6xl0^{-5}$-$1.2xl0^{-3}$	0.1 -2
5	Silt	1 $x10^{-5}$-5x 10^{-3}	$6xl0^{-6}$-$3xl0^{-3}$	0.01 -0.5
7	Clay	Less than 10^{-6}	Less than $6x10^{-7}$	Less than 10^{-3}
B.	***Consolidated material***			
1	Sandstone	10^{-6}- 10^{-3}	$6x10^{-7}$ - $6X10^{-4}$	10^{-3}-1.0
2	Carbonate rock with secondary porosity	10^{-5} - 10^{-3}	$6x10^{-6}$-$6x10^{-4}$	10^{-2}- 1.0
3	Shale	10^{-10}	$6x10^{-11}$	10^{-7}
4	Fractured and weathered rock (aquifers)	10^{-5} - 10^{-3}	$6x10^{-7}$-$6x10^{-4}$	10^{-3}- 1.0
At 20 °C, for water, v = 0.01 cm^2/s K_0 [Darcy's] = 1 0^3 *K* [cm/s] at 20 °C				

(Source: Engineering Hydrology, Second edition by Subramanya, 1994)

Appendix A-2 Pumping Test Data Analysis Methods

Method	**Condition**
Confined Aquifer	
Theim's method	Steady-state flow
Theim's method	Unsteady-state flow
Jacob's method	Unsteady-state flow
Leaky Aquifer	
De Glee's Method	Steady-state flow
Hantush-Jacob's Method	Steady-state flow
Walton's Method	Unsteady-state flow
Hantush's inflection point Method	Unsteady-state flow
Hantush's curve point Method	Unsteady-state flow
Neuman-Witherspoon's Mehod	Unsteady-state flow
Unconfined Aquifers	
Thiem-Dupuit's Method	Steady-state flow
Neumann's curve fitting Method	Unsteady-state flow
Bounded Aquifers	
Dietz's Method	Bounded confined or unconfined aquifer, Steady-state flow
Stallman's Method	Bounded confined or unconfined aquifer, Unsteady-state flow
Hantush's Method	Bounded confined or unconfined aquifer, Unsteady-state flow
Vandenberg's Method	Bounded leaky or unconfined aquifer, Unsteady-state flow
Wedge Shaped and Sloping Aquifers	
Culmination point Method	Sloping unconfined aquifer, stead-state flow
Hantush's Method	Sloping unconfined aquifer, Unsteady-state flow
Hantush's Method	Wedge shaped confined aquifer, Unsteady-state
Multi-layered Aquifer Systems	
Javandel-Witherspoon's Method	Confined two layered aquifer systems, Unstable-state flow
Bruggeman's Method	Leaky two-layered aquifer systems, Steady-state flow
Recovery Tests	
Theis's Recovery Method	Confined aquifer, after constant discharge test
Theis's Recovery Method	Leaky aquifer, after constant discharge test
Theis's Recovery Method	Unconfined aquifer, after constant discharge test
Birsoy-Summer's Method	Confined Aquifer, after variable discharge test
Large diameter Wells	
Papadopulo's curve fitting Method	Confined aquifer, Unsteady -state flow
Boulton-Streitsova's curve fitting Method	Unconfined aquifer, Unsteady state flow
Well Performance Tests	
Hantush-Bierschenk's Method	Step-drawdown test
Eden-Hazel's Method	Step-drawdown test, Confined aquifer
Rorabaugh's Method	Step-drawdown test
Sheahan's Method	Step-drawdown test
Partially Penetrating Wells	
Huisman's correction Method I	Confined aquifer, Steady state flow
Huisman's correction Method II	Confined aquifer, Steady state flow
Hantush's modification of Theis's Method	Confined aquifer, Unsteady state flow
Hantush's modification of Jacob Method	Confined aquifer, Unsteady state flow
Week's modification of the Walton Leaky aquifer, Unsteady- state flow and the Hantush curve 'fitting methods	
Strelsova's curve fitting Method	Unconfined anisotropic aquifer, Unsteady state flow
Neumann's curve fitting Method	Unconfined anisotropic aquifer, Unsteady state flow

(Source: G. P. Kmseman and N. A. de Ridder, 1994)



Appendix B-1 Isohytes for Pangani River Basin (Source: Ministry of Water-Hydrological year Book 1971-1980)

Appendix C-1 Lithological logs for Boreholes

LITHOLOGY: BH AR 225/2004

From(m)	To(m)	General Description
0	4	Clay brown
4	18	Fine sand brownish
18	24	Coarse sand
24	115	Fine sand from fractured basalt
115	120	Pebbles

LITHOLOGY: BH AR 388/2001

From(m)	To(m)	General Description
0	0.5	Top soil clay with volcanic ash brown
0.5	4	Volcanic ash with medium to coast pebble from weathered lava brownish
4	12	Pebbles with coarse sand volcanic ash-greyish brown
12	18	Fine with coarse pebble fractured weathered Lava basalt greyish
18	26	Pebbles cobbles with clay from fractured basalt greyish
26	30	Pebbles with cobbles from weathered fractured basalt greyish
30	80	No sample (due to loss of mud circulation)

LITHOLOGY: BH AR 05/2004

From(m)	To(m)	General Description
0	2	Medium coarse.
2	4	Fine medium sand.
4	28	Coarse sand with gravel and pebbles.
28	46	Basaltic chips.
46	62	Fine to medium sand with basaltic chips.
62	82	Medium coarse sand with basaltic chips.
82	124	Fine sand.

LITHOLOGY: BH AR 182/2001

From(m)	To(m)	General Description
0	4	Pebbles and cobbles with little clay.
4	6	Volcanic sand.
6	10	Pebbles and cobbles with coarse gravels.
10	14	Clay sticky, with pebbles and cobbles.
14	18	Coarse sand with pebbles.
18	20	Medium to coarse sand.
20	24	Coarse sand.
24	32	Pebbles and cobbles and coarse sand.

Appendix C-2 Lithological logs for Boreholes

LITHOLOGY: BH AR 43/2002

From(m)	To(m)	General Description
0	0.5	Top soil silt dark grey
0.5	4	Volcanic ash dark grey
4	6	Volcanic ash with fine sand brownish
6	8	Clay light grey
8	10	Volcanic fine sand with few clay
10	12	- yellowish grey
12	14	Fine volcanic sand with ash and few clay
14	16	Brownish grey
16	18	Medium coarse sand with gravel grey
18	20	Fine sand with few volcanic ash grey
20	22	Fine sand with few volcanic ash grey
22	24	Coarse volcanic sand from lava grayish brown
24	26	Coarse volcanic sand from lava grayish brown
26	28	Very fine volcanic sand with few clay
28	30	Brownish.
30	32	Coarse volcanic sand with few
32	34	Clay -brownish
34	36	Medium to coarse sand from highly
36	38	Weathered volcanic lava- dark grey
38	40	Medium coarse sand from weathered basalt
40	42	Dark grey
42	44	Coarse sand from weathered basalt dark
44	46	Grey
46	48	Fine to medium sand from weathered
48	50	Fractured basalt dark grey.

LITHOLOGY: BH AR 96/2004

From	To	General Description
0	2	Top soil, clay, greyish brown
2	6	Volcanic sand, fine greyish
6	20	Fine to medium coarse sands
20	38	Very fine to fine sand slightly weathered
38	50	Fine to medium coarse sand
50	58	Fine sand grey
58	62	Medium course sand
62	74	Fine sand grey
74	80	Medium course to course sand
80	92	Very fine sand to fine sand
92	100	Medium course sand
100	146	Fine sand derived from fresh basalt grey

Appendix C-3 Lithological logs for Boreholes

LITHOLOGY: BH AR 14/2003

From (m)	To (m)	General Description
0	1	Top soil
1	4	Clay, blackish
4	8	Clay, brownish grey
8	10	Pebbles, cobbles, mixed with coarse gravels, Light grey.
10	12	Medium coarse sand (volcanic) mixed with little gravels
12	61	Total loss of mud circulation - No samples

LITHOLOGY: BH AR445/05

From(m)	To(m)	General Description
0	2	(Top soil) fine sand brownish
2	16	Fine sand from basalt grayish
16	18	Fine sand with coarse gravel grayish
18	24	Fine sand with weathered basalt gray
24	26	Gravel with basalt light gray
26	36	Clay with fine sand grayish brown
36	42	Fine sand with basalt grayish brown
42	46	Medium to coarse sand with weathered Basalt brownish gray
46	50	Clay with gravel weathered grayish brown
50	57	Fine sand slightly weathered

LITHOLOGY: BH AR 384/2001

From(m)	To (m)	General Description
0	26	Clay (weathered volcanic rock)
26	28	Partially weathered volcanic rocks
28	32	Fractured basalt
32	34	Sand and gravel
34	54	Sand silt
54	60	Fractured basalt
60	62	Gravelly fine sand
62	72	Gravelly silt sand
72	74	Silt gravelly sand
74	76	Silt sand with occasional gravels
76	82	Sandy gravels
82	84	Slightly fractured lava
84	86	Lahar
86	90	Slightly weathered lava
90	92	Lahar
92	102	Lahar slightly weathered and fractured.

Appendix C-4 Pump test data for BH AR 43/2002

Date	Time		DWL	Drawdown	Yield m3/hr
	hrs	min	m		
8.2.2002		0	2.9	0.4	9.0
		1	5.4	2.9	9.0
		2	7.85	5.35	9.0
		3	8.4	5.9	8.9
		4	8.6	6.1	8.9
		5	8.75	6.25	8.9
		6	8.8	6.3	8.7
		7	8.9	6.4	8.7
		8	8.94	6.44	8.6
		9	9	6.5	8.6
		10	9.01	6.51	8.5
		12	9.13	6.63	8.5
		14	9.15	6.65	8.4
		16	9.2	6.7	8.3
		18	9.22	6.72	8.2
		20	9.25	6.75	8.2
		25	9.3	6.8	8.2
		30	9.35	6.85	8.0
		35	9.4	6.9	8.0
		40	9.45	6.95	8.0
		45	9.5	7	8.0
		50	9.55	7.05	8.0
		55	9.6	7.1	8.0
		60	9.63	7.13	8.0
		70	9.68	7.18	8.0
		80	9.8	7.3	8.0
		90	9.83	7.33	8.0
		105	9.9	7.4	8.0
		120	9.95	7.45	8.0
		150	9.95	7.45	8.0
		180	10.1	7.6	8.0
		210	10.15	7.65	8.0
		240	10.2	7.7	8.0
		270	10.25	7.75	8.0
		300	10.3	7.8	8.0
		360	10.35	7.85	8.0
		420	10.4	7.9	8.0

Appendix C-5 Pump test data for BH AR 690/2006

Date	Time		DWL	Drawdown	Yield LPH
	hrs	min	m		
1/12/2006	12	0	69.67	0	——
		1	78.45	8.78	5.28
		2	81.52	11.85	4.4
		3	84.37	14.7	3.771
		4	87.28	17.61	2.828
		5	90.43	20.76	2.475
		6	92.19	22.52	2.14
		7	94.54	24.87	1.841
		8	94.48	24.81	1.584
		9	97.29	27.62	1.466
		10	98.18	28.51	1.414
		11	99.04	29.37	1.389
		12	100.67	31	1.389
		14	100.99	31.32	1.389
		16	101.13	31.46	1.389
		18	101.24	31.57	1.365
		20	101.31	31.64	1.365
		9	97.29	31.7	1.466
		10	98.18	31.73	1.414
		11	99.04	31.73	1.389
		25	101.37	31.73	1.365
		30	101.4	31.74	1.365
		35	101.4	31.74	1.342
		40	101.4	31.74	1.342
		45	101.41	31.74	1.342
		50	101.41	31.74	1.342
		55	101.41	31.74	1.342
	13	0	101.41	31.74	1.298
		10	101.41	31.74	1.298
		20	101.41	31.74	1.298
		30	101.41	31.74	1.298
		40	101.41	31.74	1.298
		50	101.41	31.74	1.298
	14	0	101.41	31.74	1.298
		15	101.41	31.74	1.277
		30	101.41	31.74	1.277
		45	101.41	31.74	1.277
	15	0	101.41	31.74	1.277
		20	101.41	31.74	1.277
		40	101.41	31.74	1.277
	16	0	101.41	31.74	1.277
		30	101.41	31.74	1.277
	17	0	101.41	0	1.277
		30	101.41	8.78	1.277
	18	0	101.41	11.85	1.277

Appendix C-6Pump test data for BH AR 445/2003

Date	Time		DWL	Drawdown	Yield LPH
	hrs	mm	m		
26.7.2005	9	0	5.34	0	6.5
		1	6.3	0.96	6.5
		2	6.8	1.46	6.5
		3	6.9	1.56	6.5
		4	7.25	1.91	6.8
		5	7.5	2.16	6.8
		6	7.83	2.49	9
		8	8.1	2.76	9
		10	8.13	2.79	8.5
		15	8.16	2.82	8.5
		20	8.22	2.88	8.5
		25	8.26	2.92	8.5
		30	8.3	2.96	8.5
		35	8.55	3.21	8.7
		40	8.85	3.51	8.7
		45	9.05	3.71	8.7
		50	9.2	3.86	8.7
		55	9.33	3.99	8.7
	10	0	9.45	4.11	8.7
		10	9.7	4.36	8.8
		20	9.8	4.46	8.8
		30	9.95	4.61	8.8
		40	10.05	4.71	8.8
		50	10.15	4.81	8.8
		0	10.2	4.86	8.8
		15	10.23	4.89	8.8
		30	10.35	5.01	8.8
		45	10.46	5.12	8.8
	11	0	10.56	5.22	8.8
		30	10.86	5.52	8.8
	12	0	11.1	5.76	8.8
		30	11.26	5.92	8.8
	13	0	11.58	6.24	8.8
		30	11.75	6.41	8.8
	14	0	11.85	6.51	8.8
		30	11.91	6.57	8.8
	15	0	11.03	5.69	8.8
		30	11.06	5.72	8.8
	16	0	12.06	6.72	8.8
		30	12.06	6.72	8.8
	17	0	12.06	6.72	8.8
		30	12.06	6.72	8.8
	18	0	12.06	6.72	8.8

Appendix D-1 Borehole Data for Arusha City

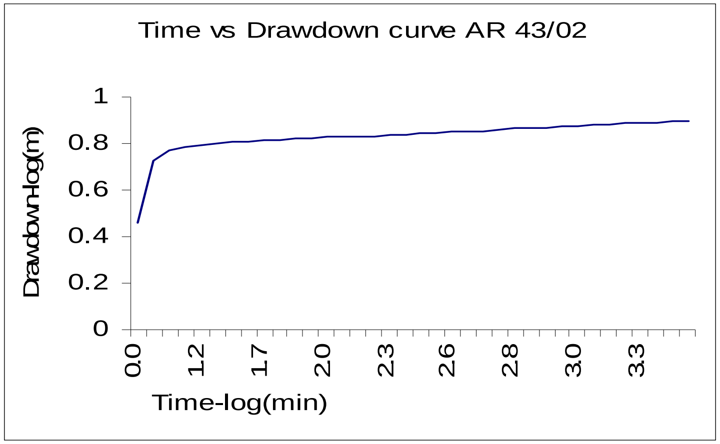
No.	Source No.	Location Name	XPR	YPR	Altitude (a.m s.l)	S.W.L (m)	Source Type	Drilled Depth (m)	BH diam- (mm)	1st W.S (m)	2nd W.S (m)	3rd W.S (m)	4th W.S (m)	Yield m3/h	Drawd own
1	AR.92/92	Tanzania Pharmathetical	245528	9624218	1290	48.98	BH	110		7-15	40-50	91-106		9.321	
2	AR.93/83	Sunflag/Themi	236075	9623933	1368		BH	104.55		76				30	Good
3	AR.79/77	Magereza	235947	9627005	1377	40.26	BH	97.6	150	29	57.03	73.2		12	
4	AR131/79	Mount Meru Hospital	243853	9627934	1409		BH	64.1		33.5	38.12	61		56.6	13.8
5	AR 24/96	Jandu Plumbers	242616	9625997	1420	26.52	BH	104		12.1 - 32	40 - 50	60 - 74	86 - 97	14.5	
9	AR.91/2001	AICC complex	243900	9627930	1430	21.5	BH	96						20	3.3
10	AR.225/2004	Njiro II	245782	9622160	1357	36.2	BH	120		4-8	18-24			9.9	13.85
11	AR.338/97	Njiro	246498	9623951	1308	5	BH	30		10-15	22-24			5.6	
13	AR.253/2007	Arusha Town	243696	9626792	1370	44.5	BH	115						1.72	23.1
14	AR.444/2003	Moshono	247421	9625807	1357	8	BH	44		12	26	32	44	2.3	30.1
15	AR.123/96	Majengo	239877	9626238	1350	6.7	BH	50		8	20			6.60	7.2
16	AR 38/2002	Sakina kwa Idd	238607	9629778	1433	15.6	BH	70		30 – 70				8.00	37.72
17	AR.339/97	Levolosi	241756	9627473	1382	10	BH	85		14-15	55-75			7.20	1.5
18	AR.690/2006	Kiranyi/Sakina	240730	9630237	1460	69.67	BH	103		40-52	60-70	80-90		1.28	31.74
19	AR.182/2004	Kanisa Road	244004	9627361	1410	10.7	BH	32		3	6	22		13.50	8.92
20	AR.87/2002	Sokoni Str.	242531	9627237	1392	2.15	BH	42		12-36				<2.6	37.25
21	AR.93/83	Sun-Flag Themi	246410	9624080	1316	32.62	BH	104.5		58 - 76				6.60	12.28
22	AR.71/98	PPF Estate Njiro	245533	9624517	1301	12.9	BH	103						7.40	26.63
23	AR 96/2004	Agr.Research Inst.	237220	9627719	1385	62.27	BH	146						9.20	0.11
24	AR 196/2004	Sari/Selian II	237796	9627844	1390	62	BH	140		53 – 64	84 – 96	107-121	133-141	16.74	1.02
25	AR.507/2005	Sombetini	237095	9623622	1322	7.8	BH	48		10	18	26	35	9.00	4.65
26	AR.91/2002	Sakina	239580	9628233	1410	33.22	BH	100		34-54	60-82			0.72	5.38
27	AR.591/2007	Selian	239073	9629059	1385	13.2	BH	35		23-37				5.28	8

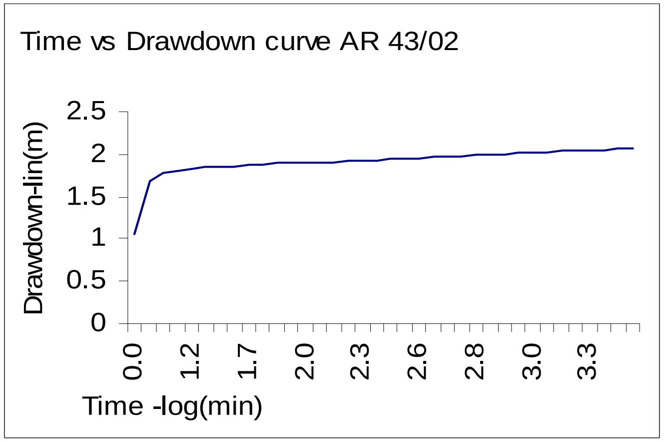
Appendix D-2 Borehole Data for Arusha City

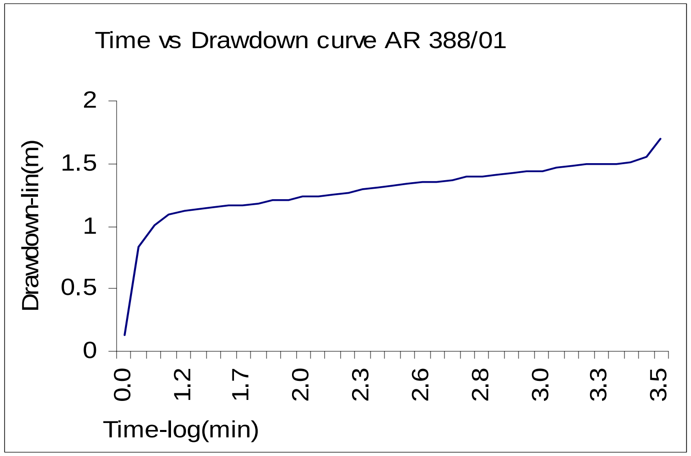
No.	Source No.	Location Name	XPR	YPR	Altitude (a.m s.l)	S.W.L (m)	Source Type	Drilled Depth (m)	BH diam (mm)	1st W.S (m)	2nd W.S (m)	3rd W.S (m)	4th W.S (m)	Yield m3/h	Draw down
28	AR. 501/2002	Mbauda	240018	9626710	1360	6.4	BH	60		8-18	24			12.00	3.74
29	AR.05/2004	Njiro	245524	9624080	1322	68.53	BH	120						10.00	
30	AR.445/2005	Levolosi	241730	9627726	1390	5.34	BH	57		10 -14	24-26	40-42	48-56	8.80	6.72
32	AR.89/93	Matevesi	235205	9627672	1380	33.88	BH	90		33-40	60-80			26.40	1.47
33	AR.43/2002	Sombetini	237826	9622546	1310	2.5	BH	54						7.76	7.5
34	AR.388/2001	M/S F.Safaris Ltd	234046	9630090	1410	31.36	BH	80		15-30				7.20	5.44
35	AR.72/71	General Tyre	235258	9624380	1365	10	BH	90.91		10				4.00	42.42
36	AR.131/79	Mount Meru Hosp.	243853	9627934	1364	Artesian	BH	64.05		33.5-38	56-61			56.69	13.83
37	AR 20/89	New Arusha	243867	9626770	1410	52.77	BH	122		52.8				5.57	1.65
38	AR.246/75	Maji Yard	241928	9627571	1383	11.59	BH	58.56		15.3	21.4	35.1		8.20	
39	AR.47/67	Emco(Maji)	244002	9625738	1371	3.1	BH	173.7		57.91	106.8			70.50	32.1
40	AR.202/98	Kilombero	244141	9625843	1470	18.98	BH	80						7.20	1.37
41		Burka I	239310	9627531			Spring								
43	AR 313/2001	Bondeni	243086	9627289	1395	7.55	BH	84	200	8.0-10.1				8.00	3.55
44	No1	Magereza area	234557	9627172	1377	24.95	BH	78						90.00	3.21
45	No2	Magereza area	234487	9626986	1377	27.72	BH	76.5						80.00	
46	No3	Magereza area	234927	9626800	1377	30.3	BH	78						78.00	4.03
47	AR 202/96	Themi estate	245692	9623620	1320	29.2	BH	54	200					1.50	
48	AR 99/77	Arusha Tech	241933	9627943	1490		BH	115.9		54	76.3	77.8		55.40	27.27
49		Ngaramdolu	241991	9627152			Spring								
50	AR 90/77	Sunflag/Themi	246410	9624080	1377	6.4	BH	42.1		7.62	19.82			36.00	16.1
51	AR /2005	Sokoni I	242725	9623570	1313	23.3	BH	62						3.60	15.32
52	349/99	Ngaramtoni (TPRI)	235686	9631931	1440	38.1	BH	89		30	33			0.80	

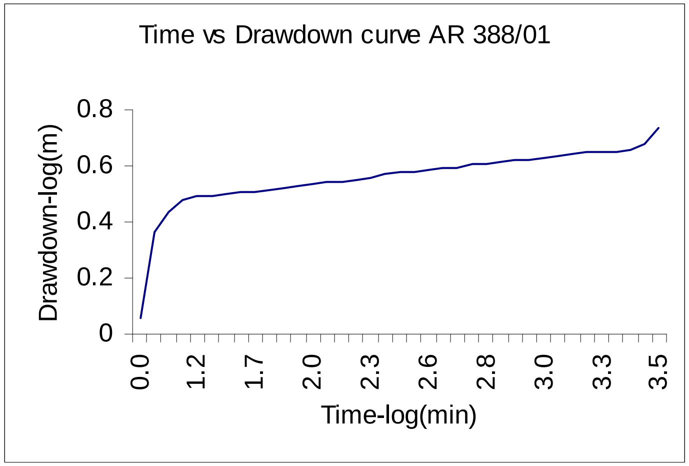
Appendix D-3 Borehole Data for Arusha City

No	Source No.	Location Name	XPR	YPR	Altitude (a.m s.l)	S.W.L (m)	Source Type	Drilled Depth (m)	BH diam-mm	1st W.S (m)	2nd W.S (m)	3rd W.S (m)	4th W.S (m)	Yield m3/h	Draw down
53	AR 161/87	Moivo II	244510	9628764	1439	2.7	BH	110		88				120	80
54	AR 51/86	Moivo I	243975	9629209	1443	16.9	BH	120		92				145.00	57.8
55	AR 60/86	Ilklorit	243205	9630092	1455	14	BH	206		114				145.00	76.4
56	AR 41/88	Oltulelet	242522	9629754	1477	37	BH	183.5		110				300.00	155
57	AR 251/76	Loruvan Bondeni	243750	9629785	1530	0.6	BH	64.1		35				120.00	2.4
58	AR 82/68	Sekei	244939	9628664	1439	10.1	BH	144.9		137				32.70	17.3
59	AR 105/70	Tengeru Com.Cent	257758	9598747	1180	19.5	BH	47.3		37				13.60	13.6
60	AR 75/86	Burka Coffee Estate	234092	9628716	1459	38	BH	119		79				9.60	13.5
61	AR 11/77	Kioga	243874	9629835	1455	21.4	BH	67.1		44				36.00	28.8
62	AR 163B/73	Patandi	255383	9627424	1250	24.6	BH	70.8						10.30	2.2
63	AR 216/74	Loruvan	244477	9631313	1477	10.9	BH	91.7		33				46.80	50
64	AR 92/78	Sakina South	240638	9628060	1409	9.3	BH	90.3						55.40	27.3
65	AR /2002	A-Z Factory	242639	9625628	1354	8.4	BH	80		8-11	18-22	30.36		7.00	51.2
67	AR 92/78	Sakina South	240638	9628060	1409	9.3	BH	90.3						55.40	27.3
68	AR /2002	A-Z Factory	242639	9625628	1354	8.4	BH	80		8-11	18-22	30.36		7.00	51.2

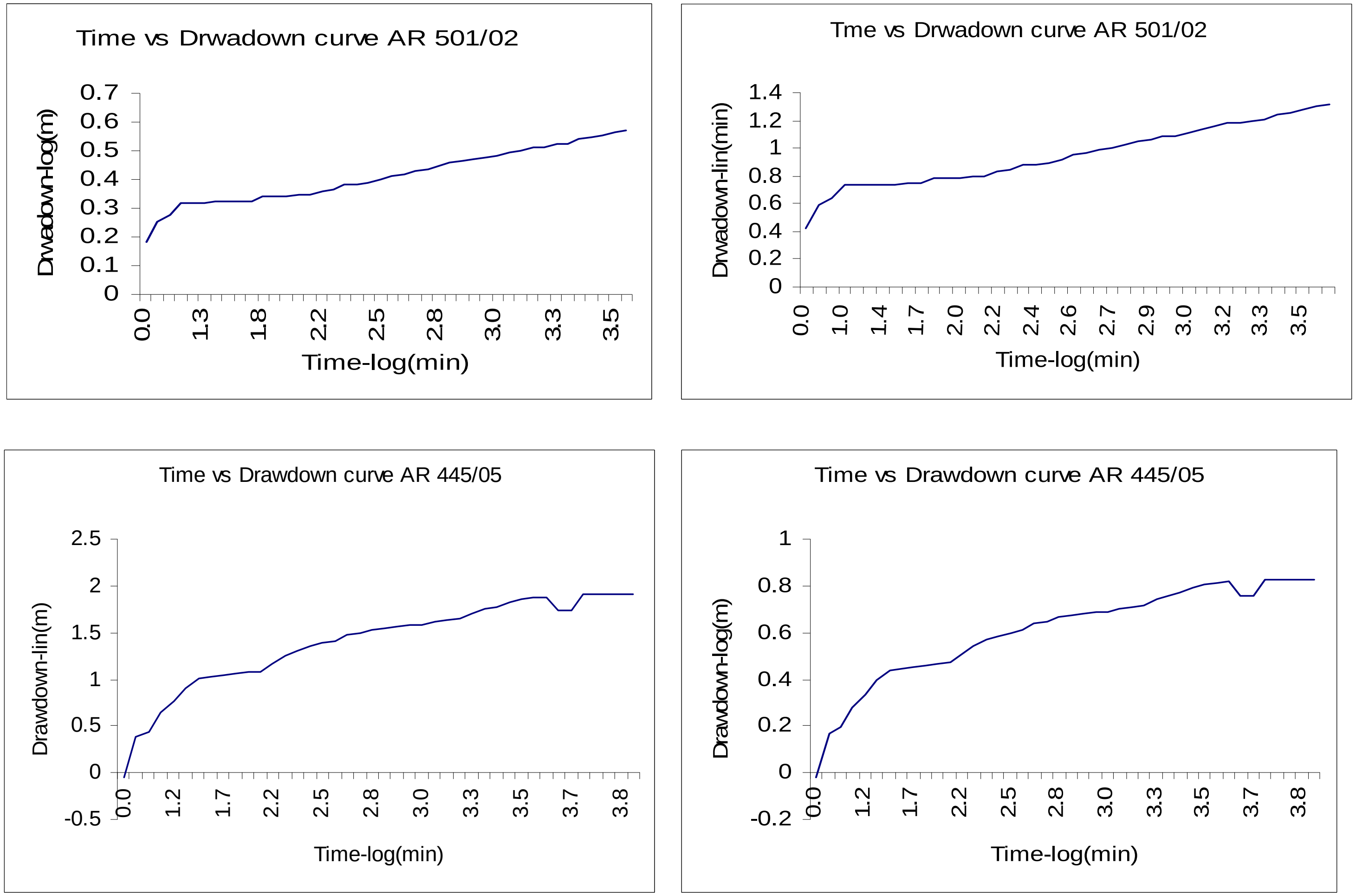




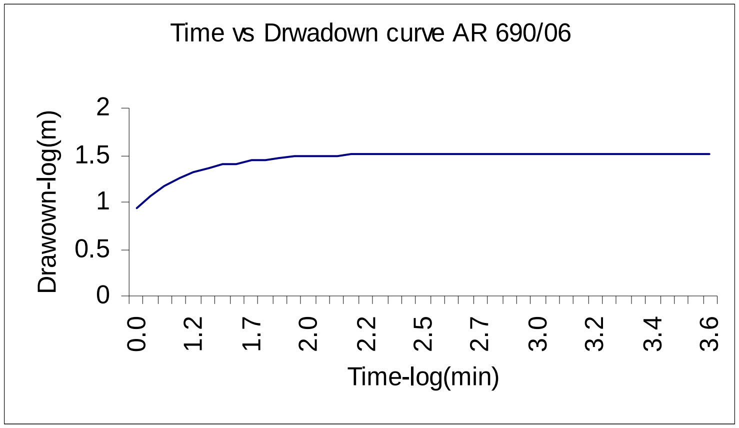


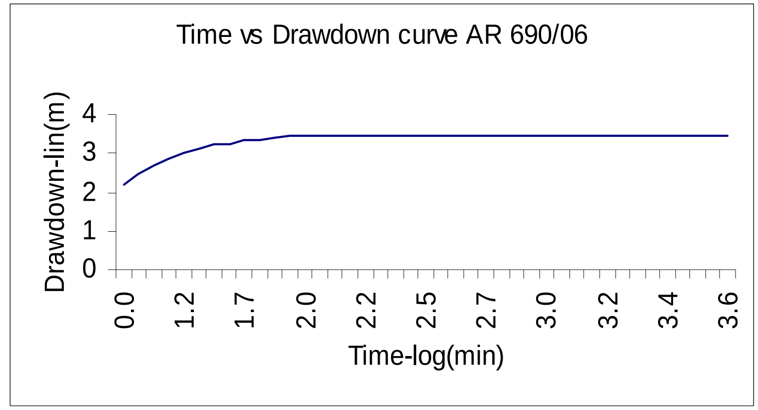


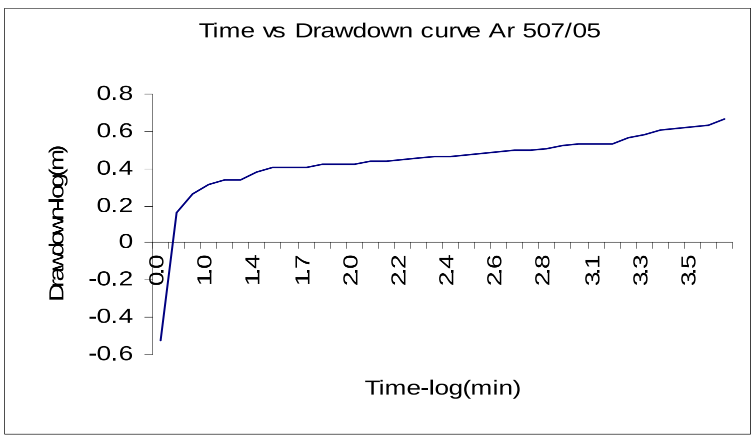
Appendix E-1 Time vs. drawdown curves for few boreholes for Arusha city

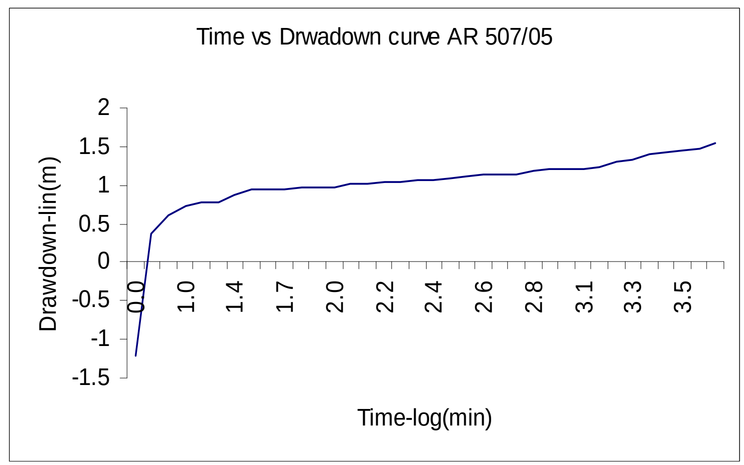


Appendix E-2 Time vs. drawdown curves for few boreholes for Arusha city









Appendix E-3 Time vs. drawdown curves for few boreholes for Arusha city