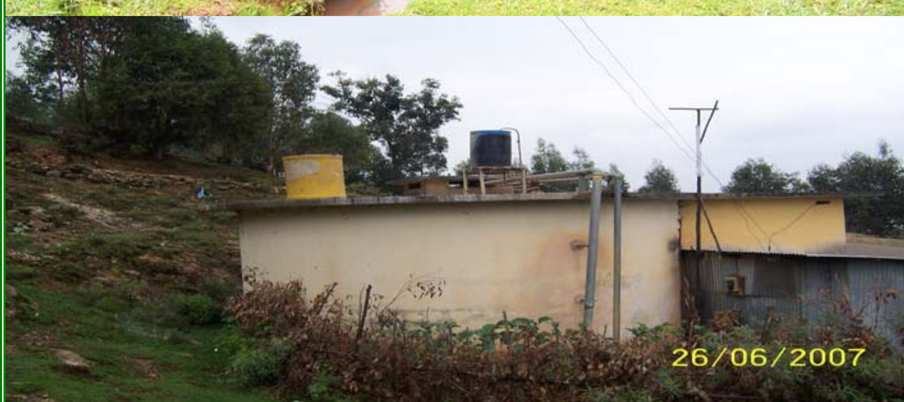
ADDIS ABABA UNIVERSITY
School of Graduate Studies
Department of Earth Science

ANALYSIS MODELS OF THE EMPTYING CURVES OF FIVE SELECTED SPRINGS IN ADDIS ABABA



In partial fulfillment of the requirements for the Degree of Masters in Hydrogeology

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July, 2007

ACKNOWLEDGEMENTS

I would like to thank Dr. Tamiru Alemayehu, my advisor and instructor, for his unreserved advice, follow up and kind provision of reading materials. I am grateful to the supports of Dr.Tarun K.Raghuvanshi, my Engineering Geology instructor, for his positive attitude towards helping students, providing his expertise any time and any place.

My sincere thanks goes to Ato Seyoum Desta, General Manager of Addis Ababa Water and Sewerage Authority, who has kindly facilitated this chance of post graduate study. My appreciation and thanks is also to Yirga Tadesse, my office supervisor, for his critical technical advices and brotherly help. All staff members of my Department and the Central Laboratory of AAWSA are also acknowledged for their valuable support. I am indebted to the contributions of Seyoum Abebe for his uninterrupted help during field works.

My wife, Ayalsew Gebresilassie and all family members; Diffe Mekonnen, Tsehay Waltenigus and Banchi Waltenigus also deserve special thanks for their daily support and encouragements. My all time friends Kebede Fekede, Dr. Asfawossen Asrat, Abinet Gebremedhin, Selamawit Mussie and Tafach (wubet) have also been by my side doing their best to help me. A very special thanks is to Daniel Semmere, for his priceless support and encouragement from abroad.

I genuinely appreciate my class mates, all of which have been good to me and kindly sharing their experiences. My admiration and thanks is also to my friend Aychiluhim Debebe, who has been sharing his talent, experience and anxiously following up my study progress. Leta Gudissa, a friend from the same Department, is acknowledged for his provision of important reference materials.

Above all, my gratitude and thanks to God, for being with me from the beginning to the end of everything I did.

Abstract

The use of springs as a community water supply source in Addis Ababa dates back to the very early times of the establishment of the city. Other surface and ground water sources (dams and water wells) have also been constructed in its later development stage. No matter how big the newly developed sources are, it is true that spring sources are still in use. This justifies the importance of these sources as a means of potable water supply and invites for further detail investigations.

Identification of springs with sustainable flow has been a pre requisite prior to construction. Analytical flow modeling of springs with has a lot to provide in answering this question as it helps to understand the flow and storage conditions of a spring source.

In this study an attempt was made to analyze the emptying curves of six springs in Addis Ababa of which collected data have permitted the analysis of five of them. The analysis is based on monthly discharge monitoring of the springs for one hydrologic year. Water sampling has also been conducted from each spring for the determination of seasonal water quality changes. Recession curves were identified from the plot of the monthly spring discharge, from which flow and storage parameters were calculated. The main parameters of the sources have been estimated using the formula developed by Mangin (1970).

From the analysis of the curves, it was possible to extract information on the contribution of rainfall to the spring discharge, storage conditions of the spring reservoir, the recharge conditions (rate of recharge) and the current reserve for sustainable flow. The method is applicable even to very small discharge springs. This has been considered as a means of identification of sustainable springs prior to construction.

DECLARATION

I, the undersigned, declare that this thesis is my original work and has not been presented for a degree on any other university.

All sources of materials used for the thesis have duly acknowledged.

SOLOMON WALTENIGUS

signature_________________________

Place and date of submission: School of Graduate Studies, Addis Ababa University, July 2007.

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CHAPTER ONE

INTRODUCTION

1.1 GENERAL

The survival of life on the planet Earth is highly dependent on the existence of water that is available on or beneath the surface. Surface water is often in close contact with human activities and/or other domestic and wild animals; hence is vulnerable to pollution that makes it unsuitable for drinking and other purposes before treatment. On the other hand, groundwater has minimal risk of pollution as compared to surface water, for the reason that it is naturally devoid of direct contact with the activities carried out on the surface. There are also a number of natural protection mechanisms for the indirect threats to it. Consequently, where waters are available in their natural conditions both from surface and groundwater sources at a time, people tend to use the groundwater sources more preferably.

Groundwater can be made available on the surface either naturally (in the form of springs) or artificially (by means of pumping). A spring is a place on the earth's surface where groundwater emerges naturally. The water source of most springs is rainfall that seeps into the ground uphill from the spring outlet. Spring water moves down gradient through soil or cracks in rocks until it is forced out of the ground by natural pressure. The amount, or yield, of available water form springs may vary with the time of the year/s and rainfall.

Springs are susceptible to contamination because the water feeding them typically flows through the ground for only a short distance, limiting the amount of natural filtering that can occur. Springs may not be a good choice for a water supply if the area uphill where the water collects is used for industry, agriculture, or other potential sources of pollution.

Springs have long been used in Addis Ababa as a dependable water source for drinking and other domestic purposes. This dates back to 1942, the very early times of the establishment of the city ("Wuha Lehiwot", AAWSA magazine, Special Edition, July 2001, Vol III, No. 1).

Despite the fact that the city has now dramatically expanded and becomes not only the largest commercial and industrial center in the country but also center for many international organizations, even small-yield springs are still in use as supplemental water supply sources to the dwellers that live in the periphery of the city. However, the majority of the supply is obtained from surface water sources (dams) and boreholes in the city.

The modeling of the emptying of a source is extremely important for the determination of the governing conditions of the system, the type of infiltration and the duration of emptying. Among the springs still in use, modeling of the emptying curves has been applied on five of them. The springs are situated in different geo-hydrologic settings representing the northern, the central and southern parts of the city. They lie on the North-East, North-West and South-East topographic sheets of Addis Ababa. In this job, the main parameters of the sources have been estimated by means of the formula of Mangin (1970).

1.2 OBJECTIVES OF THE STUDY

1.2.1 GENERAL OBJECTIVE(S)

The ultimate objective of this project is to perform analytical modeling on selected springs found in different parts of Addis Ababa so that determination and/or prediction of a given parameter is possible at any given time in the course of the spring's life time.

1.2.2 SPECIFIC OBJECTIVES

Within the framework of the mentioned general objectives, the following specific objectives have been considered:

- Identification of the type of spring.
- Delineation of the spring physiographic basin.
- Estimation of renewal (recharge) rates at each of the spring catchments.
- Understanding of the groundwater system associated with the springs (the recharge area, the aquifer system and the discharge condition) for possible estimation of the total reserve stored in the aquifer.
- Comparison of the areal extent of the hydrographic basins of each spring with its hydro-geologic basin.
- Determination of main input parameters of the springs for the analytical model.
- Determination of the type of infiltration and duration of emptying.

1.3 RESEARCH METHODOLOGIES

- ✓ Literature review as to all possible existing spring types and their peculiar characteristics in relation to their mode of existence.

- ✓ Characterization of the hydrogeological conditions based on both primary and secondary data sources.
- ✓ Characterization of the temporal and/or spatial discharge variability of the springs.
- ✓ Characterization of seasonal water chemistry at each spring site.
- ✓ Delineation by digitization of the physiographic basin of each spring from at 1:50,000 scale topographic map.
- ✓ Comparison of the spring aquifer with the borehole logs near by, if any.
- ✓ Application of EXCEL-based iterative analytical technique for quantitative evaluation of the different parameters that characterize the spring flow.
- ✓ Applications of remote sensing, geographic information systems and other appropriate application software for data manipulation and analysis.

1.4 PREVIOUS WORKS

No single local research work was found on Modeling of springs using the analytical models of Mangin and Maillet except the one that has been done by Dr. Tamiru Alemayehu (Tamiru A., 1998) in a foreign language (Italian). Apart from this, limited numbers of similar works that are directly or indirectly related to the project content have been obtained from internet sources:

- **Amit et al., (2002).** Interpretation of spring recession curves. Groundwater (40): 543-551.
- **Berhanu Gizaw, (2002).** Hydrochemical and Environmental Investigation of the Addis Ababa Region, Ethiopia. Ph. D. Thesis, Ludwig-Maximilians-University of Munich.

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- **Fetter, (1995).** Applied Hydrogeology, Fourth edition.
- **Gentry, W Miles, Burbey, Thomas J., (2004).** Characterization of Groundwater Flow from Spring Discharge in a Crystalline Rock Environment, Journal of American Water Resource Association (JAWRA) 40(5):1205-1217.
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- **Mangin A. (1970).** Contribution a l'étude des aquifers karstiques a partit de l'analyse des courbes de décrue et tarissement. Ann. De Speleo. 25(3):581-610.
- **Ognjen Bonacci, (1993).** Split University, Croatia. Karst Springs Hydrographs as indicators of Karst aquifers, Hydrological Sciences Journal 38,1,2/1993.
- **Sanna F., (1995)**. Individuazione di importanti riserve idriche strategiche nel supramonte di Oliena-Orgosolo-Urzulei (Sardegna centro- orientale). Tesi di Dottorato. Università di Cagliari (Dipartimento di Ingegneria del Territorio) e Politecnico di Torino (Dipartimento diGeorisorse e Territorio).

- **Tamiru Alemayehu, (1998).** Comportamento idrogeologico delle strutture vulcaniche Modellistruturali sardi ed etiopia. Ph.D thesis, Turin Polytechinic, Italy.
- **Zurawska G. (2001).** Hydrogeological study of springs on geologically and tectonically complex area in Poland.

CHAPTER TWO

DESCRIPTION OF THE STUDY AREA

2.1 LOCATION AND ACCESSIBILITY

All the springs included in this study are located in and around Addis Ababa, the capital of Ethiopia. The city was founded in 1871 at the western shoulder of the Main Ethiopian Rift. The city has been widening from time to time to attain the current aerial extent of about 1,500 Km^2, that is geographically bounded by UTM coordinates of about 978000N, 1005500N and 456000E, 495000E (fig 2-1).

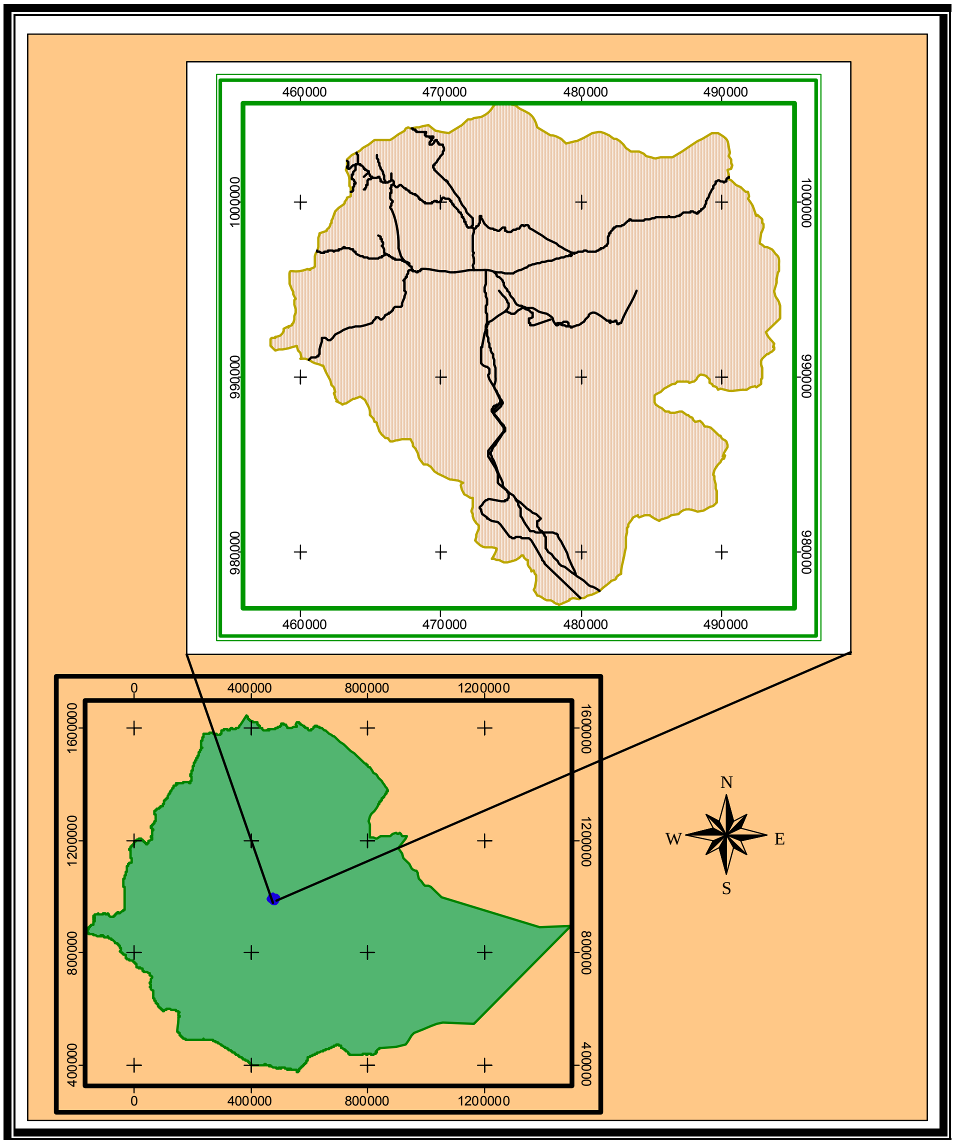

Fig 2-1: Location map of Addis Ababa

2.2 PHYSIOGRAPHY

Two rivers cross Addis Ababa from north to south. The rivers are the big Akaki river, draining the eastern part, and the Tinshu (or Little) Akaki, draining the western portion. A lot of perennial and intermittent rivers join both big Akaki and little Akaki rivers that later flow together to Awash river.

In Addis Ababa, elevation ranges generally between 1780m and 3380m a.m.s.l. However, the portion of the area with elevation greater than 3200 m a.m.s.l is negligibly small. A considerable portion of the northern part is within the elevation range of 2670m and 3000m a.m.s.l. This area is very sloppy. However, both elevation and slope decreases progressively towards the south. A large portion of the central part of the project area falls in a narrow elevation range of 2313 and 2491m a.m.s.l. Proceeding further south wards, the topography becomes very gentle and a very wide area falls under a smaller elevation range of 1958m and 2135m a.m.s.l. The lowest elevation is found at the southern border of the project area which is about 1780m a.m.s.l.

Apart from the Entoto mountain range that marks the northern border of the city, other mountainous volcanic centers also occur in the western, south western and south eastern borders. These mountains are Wechecha (3,391m a.m.s.l), Furi (2484m a.m.s.l) and Yerer (3,100m a.m.s.l). Generally, undulating to flat topography is dominant within the city boundary (fig 2-2).

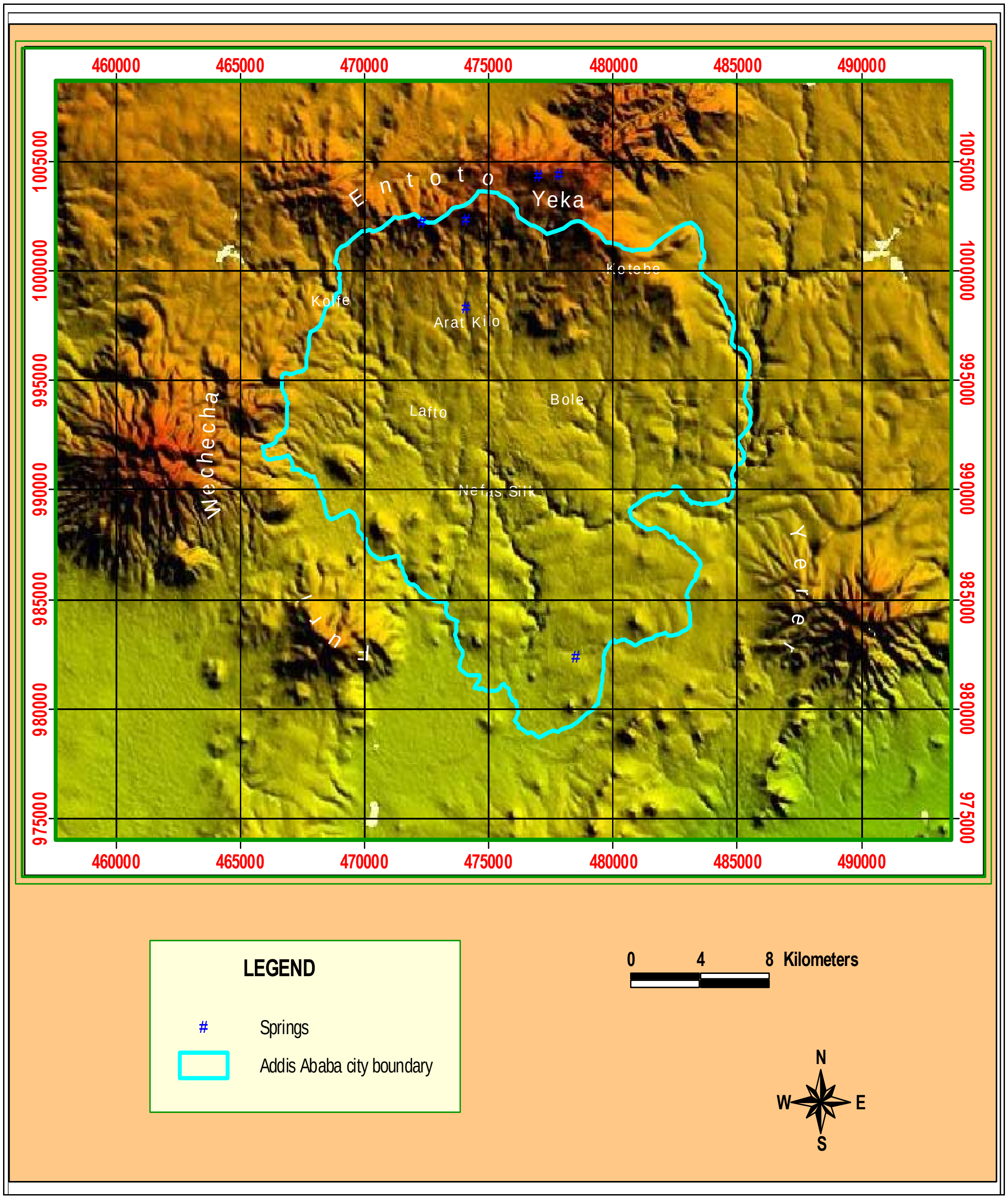

Fig 2-2: Physiographic map of Addis Ababa

Springs and rivers have been the oldest water sources of the city, though big dams and well fields have now taken over the largest share of water supply service. The springs that have been dealt with in this study are situated in different geo-hydrologic settings representing the northern, the central and southern parts of the city. They lie on the Northeast, Northwest and Southeast topographic sheets (1:50,000 scale) of Addis Ababa.

The local names of the springs, their geographic coordinates (UTM) and the topographic map on which they lie, are described in Table 2-1, and the location map of the springs with their respective delineated physiographic catchments are given in fig 2-3.

No.	**Name**	**X**	**Y**	**Z**	**Topographic Sheet**
1	Gojam-Ber Spring	470750	1003800	2840	NW
2	Akako Spring	477450	1006250	3140	NE
3	Entoto Spring	473275	1003953	2840	NE
4	Fanta Spring	479600	981100	2140	SE
5	Ras Mekonnen Spring	473262	999303	2465	NE

Table 2-1: Geographic Location of the studied springs.

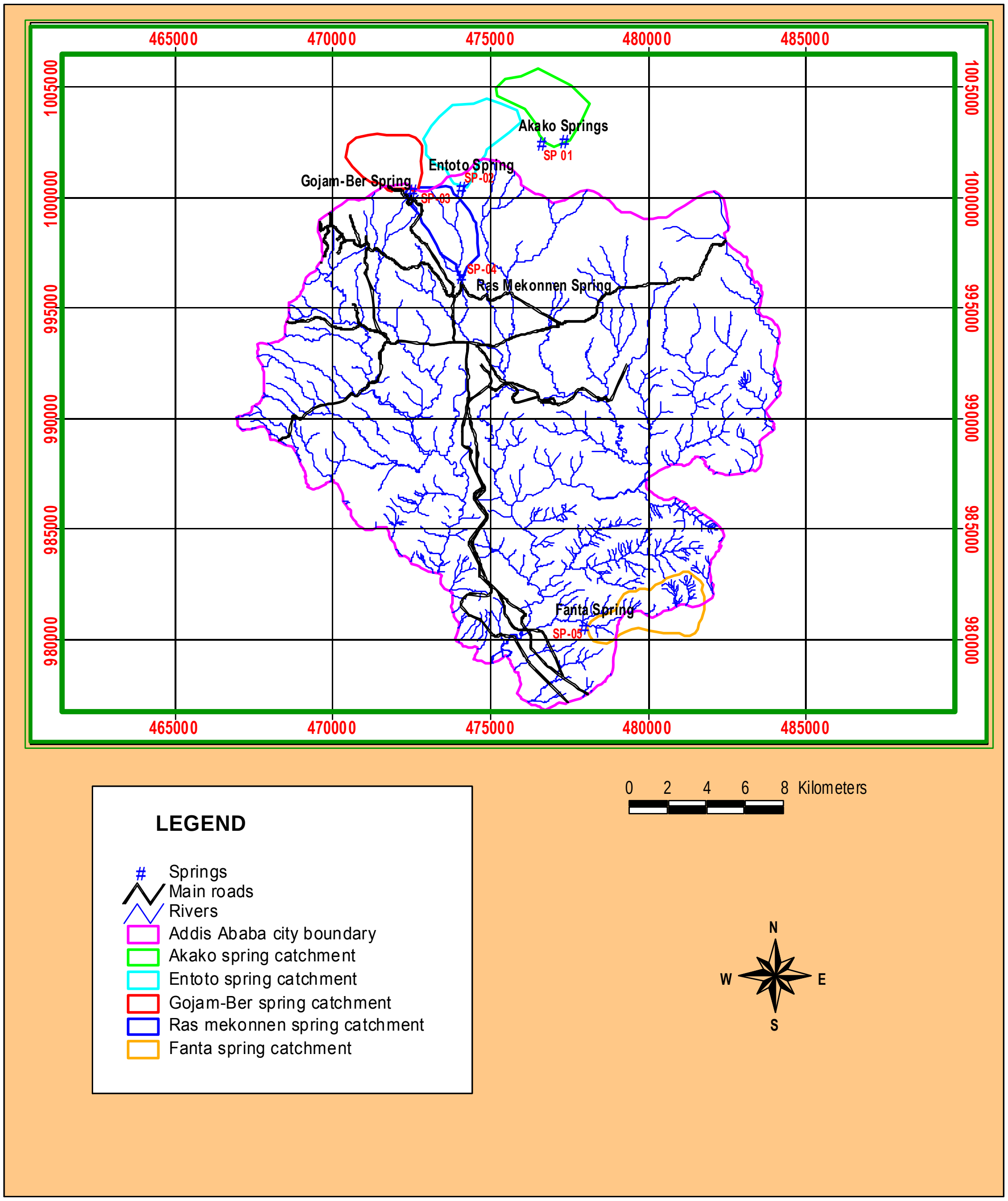

Fig 2-3: Location map of the springs and catchments

CHAPTER THREE

GEOLOGY

3.1 REGIONAL GEOLOGY

The orogenic belts of the Arabian Nubian shield and the Mozambique belt are believed to be more prominent in outcrop in Ethiopia than in any other country of the horn of Africa (Kazmin, 1972; Berhe, 1990). However, the rocks belonging to these orogenic belts are only exposed in a few areas, which have not been affected by Cenozoic volcanism and rifting, and where the phanerozoic cover rocks have been eroded away (Tefera et al, 1996).

Mohr (1963) attempted to divide the Cenozoic rocks of Ethiopia in to the trap and Aden series. The term trap series is still widely used to represent the whole pile of tertiary flood basalt sequences, which form the north-western and south-eastern plateau and attain a thickness of up to 3km (Tefera et al, 1996). The term Aden series was used for post-rift (middle Miocene- quaternary) volcanic rocks of the main Ethiopian rift afar depression, and some parts of the Ethiopian plateau.

The great east African rift system started to develop in Miocene. Rifting began from the presently oceanic red sea and Gulf of Aden rifts, which joins with the younger and continental Main Ethiopian Rift (MER) at the complex proto-oceanic Afar triple junction (Afar Depression). According to Kazmin et al, (1980), initial sagging of the MER started about 15ma and was followed by major episodes of rifting at 10ma, 5ma, 4ma and 1.8 to 1.6ma. Each stage of rifting and down faulting was accompanied by bimodal (felsic-mafic) volcanism in the rift and formation of basaltic and trachytic shield volcano on the rift shoulder and margins. This rifting resulted in a physiographic setup that incorporates highlands, escarpment and rift (low land). Eventually Addis Ababa happens to fall on the western margin of the main Ethiopian rift.

According to the general geological description of the Awash River basin (Tenalem Ayenew, et al., 2007), most of the highlands are covered with early Cenozoic Trap Series volcanics (dominantly basalt, rhyolite and ignimbrite) and the rift with acidic volcanic of the Nazreth Group and a relatively younger basic volcanics of the Afar Group (Zanettin et al., 1980). The rift floor plains are often covered with thick lacustrine and alluvial deposits.

Precambrian basement complex, Mesozoic sedimentary rocks and Cenozoic volcanics associated with Quaternary deposits are also present in the basin. The Precambrian rocks are high-grade gneisses and migmatites. The Mesozoic sequence includes the Adigrat Sandstone, the Hamanlei Formations consisting of mainly dolomites and limestones and the Amba Aradam Formation consisting of sandstones, shales and marls. The Cenozoic volcanics include the Ashangi Group, which is part of the Trap series volcanics. In the upper part of the Ashangi Group, inter-flow deposits in the form of lacustrine clays and sands, and lignite beds are also present. Post Ashenghi volcanics includes the Magdela Group, which include acid tuffs, mostly ignimbrites, rhyolites and trachytes. Basalt lavas and basic agglomerates are inter-bedded throughout and are most prevalent in the upper part. In the Afar plains, a basaltic lava sequence (Afar Group) is extensively developed. The volcanic materials occur inter-bedded with the pediments. Extruded through these lavas are ignimbrites, rhyolites and trachytes. The other more recent formation is the Wonji Group, which covers much of the floor of the Awash between Nazreth and Awash Station. The group is extremely varied in composition with rhyolites and ignimbrites dominating. The Quaternary sedimentary deposits are extremely variable both in composition and thickness. They include lacustrine deposits, clays, shales and alluvio-colluvial deposits.

All the rocks are faulted in the rift and adjacent rift escarpments. The rift is distinctly separated from the plateaux by a series of step-faults. A major fault running E-W via Kesem river-Addis Ababa-Ambo cuts across the western rift escarpment and uplifted its northern block (Zanittin et al, 1978) about 8 My ago. This fault marks the outer boundary of the western Ethiopia rift margin immediately north of Addis Ababa - Ambo (Zanittin et al, 1974).

3.2 LOCAL GEOLOGY

The area that covers the city of Addis Ababa and/or the Akaki river catchment consists of various volcanic rock units of different composition and age. Following a traverse from North (Entoto Mountain) to South (Kaliti-Akaki area), the geological formations change from the oldest volcanic sequences to the youngest. The volcanic stratigraphic sequence of Addis Ababa area has been proposed by many researchers. Haileselassie Girmay and Getaneh Assefa (1989) proposed the stratigraphy of the area starting from Sululta to Nazareth, based on Morton's geological map, unpublished student reports, K/Ar absolute age determination taken from different literatures and fieldwork to clarify some geological uncertainties. They redefine the lithostratigraphic units and modified the existing stratigraphic sequence. Accordingly, the suggested Miocene-Pleistocene volcanic succession in the Addis Ababa area from bottom to top are: Alaji rhyolites and basalts, Intoto silicics, Addis Ababa basalts, Nazareth group, and Bofa basalts.

ALAJI BASALTS

The Alaji group volcanic rocks (Alaji rhyolite and Basalt) in this part of the escarpment were outpoured from the end of Oligocene until middle Miocene (Zanettin et al., 1974), extending from the crest of Entoto mountain (Northern part of Addis Ababa) towards the north (Haileselassie Girmay and Getaneh Assefa, 1989). This unit is composed of basalts, which show variation in texture from highly porphyric to aphyric with intercalations of gray and glassy welded tuff. This unit is underlain by tuffs and ignimbrites. The stratigraphic relationship of this unit with the Entoto silicics is difficult to determine as they occur in a fault contact. Mohr (1967) proved that the Entoto trachyte overlies the Alaji basalt. The age of the rock is 22.8 M.Y (Morton et. al., 1979).

ENTOTO SILICICS

These early Miocene age silicic volcanics could represent localized terminal episodes to massive Oligocene fissure-basalt activity in the Addis Ababa region (Morton et.al. 1979). The thickness of the flow becomes maximum on the top of Entoto ridge and thin both towards the plateau and the plain east of Addis Ababa. According to Zanettin and Justin-Visentin (1974) these lavas make up a thick pile of flows accumulated along east west fissures (east-west fault running from Kessem river to Ambo) and uplifted northwards. The unit is unconformably overlain by Addis Ababa basalt on the foothill of Entoto and underlain by Alaji basalt.

The Entoto silicics is composed of rhyolite and trachyte with minor amount of welded tuff and obsidian (Haileselassie Girmay and Getaneh Assefa 1989). The rhyolitic lava flows outcrop on the top and the foothills of the Entoto ridge, predominantly in the western side. It also outcrops in the eastern part of the town from the Kokebe Tsebah School to the Benin Embassy. The thickness is quite variable as it frequently forms dome structure. In this rock unit flow banding, folding and jointing are common. The rhyolites are overlain by feldspar porphyritic trachyte and underlain by a sequence of tuffs and ignimbrites. Tuffs and ignimbrites are welded and characterized by columnar jointing. The rhyolite made up of phenocrysts of plagioclase and altered rebeekite in a groundmass of glass with iron oxide.

The trachytic lava flows outcrop on the top of Entoto ridge and its foothills. The thickness varies and reaches the maximum of 30m nearby Kotebe covering the rhyolitic lava flows. It shows a quite uniform texture, and is constituted by phenocrysts of oligoclase, sandine and rebeckite within a groundmass of plagioclase, iron oxide and minor quartz and mafic minerals. Two varieties of trachytic lava flows have been identified in the eastern side of the town, near Kotebe: a pale gray and a pink trachyte. The latter one is characterized by veins of hematized opal and by feldspar phenocrysts, which are often completely or partially altered with fine fractures filling of hematite (Varnier et al., 1985).

The Entoto silicics are dated 21.5my by Morton (1974) and 22 my by Morton et al. (1979). Thus from the general stratigraphy established by Zaneitin et al. (1974) both rhyolite and trachyte of the Entoto silicics belong to the “Miocene Alaji Rhyolite and Basalt” sequences.

ADDIS ABABA BASALT

The oldest rock post-dating the Entoto silicics is the Addis Ababa basalt. These units, which are mainly present in the central part of the town, are underlain by the Entoto silicics and overlain by Lower welded Tuff of the Nazareth group. The maximum thickness exceeding 130 meters was found at kechene stream. It is porphyritic in texture, composed of labradorite, - bytownite, olivine and augite as phenocrysts. The ground mass is made of andesine, labradorite, olivine, magnetite and pyroxene (Haileselassie Girmay and Getaneh Assefa 1989).

Olivine porphyritic basalts outcrop in the central part of the town that includes Merkato, Teklehaymanot and Sidist Kilo areas. The distribution of plagioclase porphyritic basalt is almost the same as that of the olivine prophyritic basalt, but only little more northwards. It outcrops in an area, which includes Sidist Kilo, General Winget School and French Embassy. The thickness of the olivine porphyritic basalt varies from 1m or less in the foothills of Entoto, Lideta Airfield and Filwoha to greater than 130 meters at Ketchane stream (Morton, 1974; Varnier et al., 1985). The Lower Welded Tuff overlies both types of basalt nearby the Building College, the Kolfe Police School, the Kokobe Tsebah School and Yeka-Mariam Church. On the other hand, only in the gorge of the Kechane stream the olivine pophyric basalt is overlain by the plagioclase porphyritic basalt, while elsewhere the relation ship between them is very difficult to determine (Varnier et al., 1985). Age determinations for the Addis Ababa basalt give about 7my and seem to have no time/composition equivalent (Morton et al., 1974).

NAZARET GROUP

The units identified in this group denoted as Lower Welded Tuff, Aphanitic basalt and Upper Welded Tuff. The group is underlain by Addis Ababa basalt and overlain by Bofa basalts. The rocks outcrop mainly south of Filwoha fault and extend towards Nazareth.

Lower Welded Tuff

This rock outcrops as small discontinuous body in Filwoha, western parts of Addis Ababa and Sululta. It is glassy with abundant fiamme and has columnar joints. Generally it is overlain by the aphanitic basalt and underlain by the olivine and plagioclase prophyritic basalt. The age of this rock as dated by Morton et al. (1979) at Addis Ababa and Sululta is 5.1 and 5.4 million years respectively. This age overlap with the period of the activity of Wachecha trachyte volcanoes, dated 4.6 million years. Wachecha is located 15 km west of Addis Ababa and probably the sources of the Lower welded tuff at both localities (Morton et al., 1979).

Aphanitic Basalt

This basalt covers the southern part of the town, especially the areas of Bole International Airport and Lideta Airfield. The rock body shows vertical curved columnar jointing together with sub-horizontal sheet jointing. Kaolin, lenses are present at the contact of this basalt with the younger ignimbrite. This is a sure evidence for the hydrothermal alterations along a NE-SW fracture system, which may affect both the basalt and the Entoto trachyte. Moreover the basalt is overlain by pumeacoues pyroclastic falls and the pyroclastic falls. It is underlain by a soil horizon that covers the plagioclase porphyritic basalt and overlain by soil horizon and tuff layers that lie below the young ignimbrite. It consists of labradorite, augite, rarely olivine and magnetite. The crystals of plagioclase show marked flow alignments. The age of the basalt in Addis Ababa ranges from 3.4 to 3.6 million years (Morton, 1974).

Trachy-basalt outcrops around Repi and nearby General Wingate School. It is underlain by the plagioclase and olivine porphyritic basalt and overlain by the younger ignimbrite from which it is separated by tuffs and agglomerates. Its relation with the rocks of the group is not clear, but probably younger than the aphanitic basalt (Getaneh et al., 1985). Moreover, phenocrysts that occur mainly in the rock are: sandine, labradorite, magnetite and augite.

Upper Welded Tuff

This rock outcrops all over the southern part of the town including Bole, Nefas Silk and Railway station; nevertheless it is also present in the central and northern parts of the town. It is gray colored, vertically and horizontally jointed and composed of sandine, anorthoclase, rebecite, quartz, pumice and unidentified volcanic fragments (Getaneh Assefa et al., 1989). The welded tuff is underlain by aphanitic basalts and overlain by young olivine basalts. Age determinations made on a sample collected near by Haile Gebreselassie road resulted 3.2 million years, that overlap with the activity of Yerer trachytic volcanos (Morton et. al., 1979).

YOUNG TRACHYITIC FLOWS

This rock is predominating in the southwest part of the town towards Furi and Repi along the hills and foothills of Hana Mariama and Tulu Iyou. It is porphyritic with phenocrysts of plagioclase (albite-oligoclase) sandine, biotite within a groundmass of microlities of feldspar.

It is underlain by the tuff that covers the young ignimbrite and overlaying by alternating flows of plagioclase porphyritic basalt and rhyolite especially in the Repi hill. Its relation with the young olivine prophyrytic basalt is not clear as they outcrop in different parts of the areas, however, in a small outcrop nearby Aba Samuel Lake south of the project area, the trachyte underlies the olivine porphyritic basalt.

YOUNG BASALT AND ASSOCIATED SCORIA CONES

They outcrop southward from Akaki River where they appear in the form of boulders reaching a thickness of 10 meter. Vesicles are common features observed on these rocks. They are restricted and dominant in the southeast part of the town along the Debre Zeit Road. They contain phencorysts of plagioclase, olivine that is partially and completely altered to iddingisite and augite within a groundmass composed of plagioclase magnetite pyroxene and olivine. This basalt is underlain by the tuffs, which cover the welded tuff. The age of this basalt is 2.8 My.

The basaltic lava and cinder cones exist towards the southern most part of the city along with the vesicular basalts. Some of them situated to the southeast and northeast of the Akaki wellfield seem to have erupted through these fractures as they are concentrated along the major NE - SW trending fault systems of Akaki and Dukem areas. General geological map of Addis Ababa is shown in fig. 3-1.

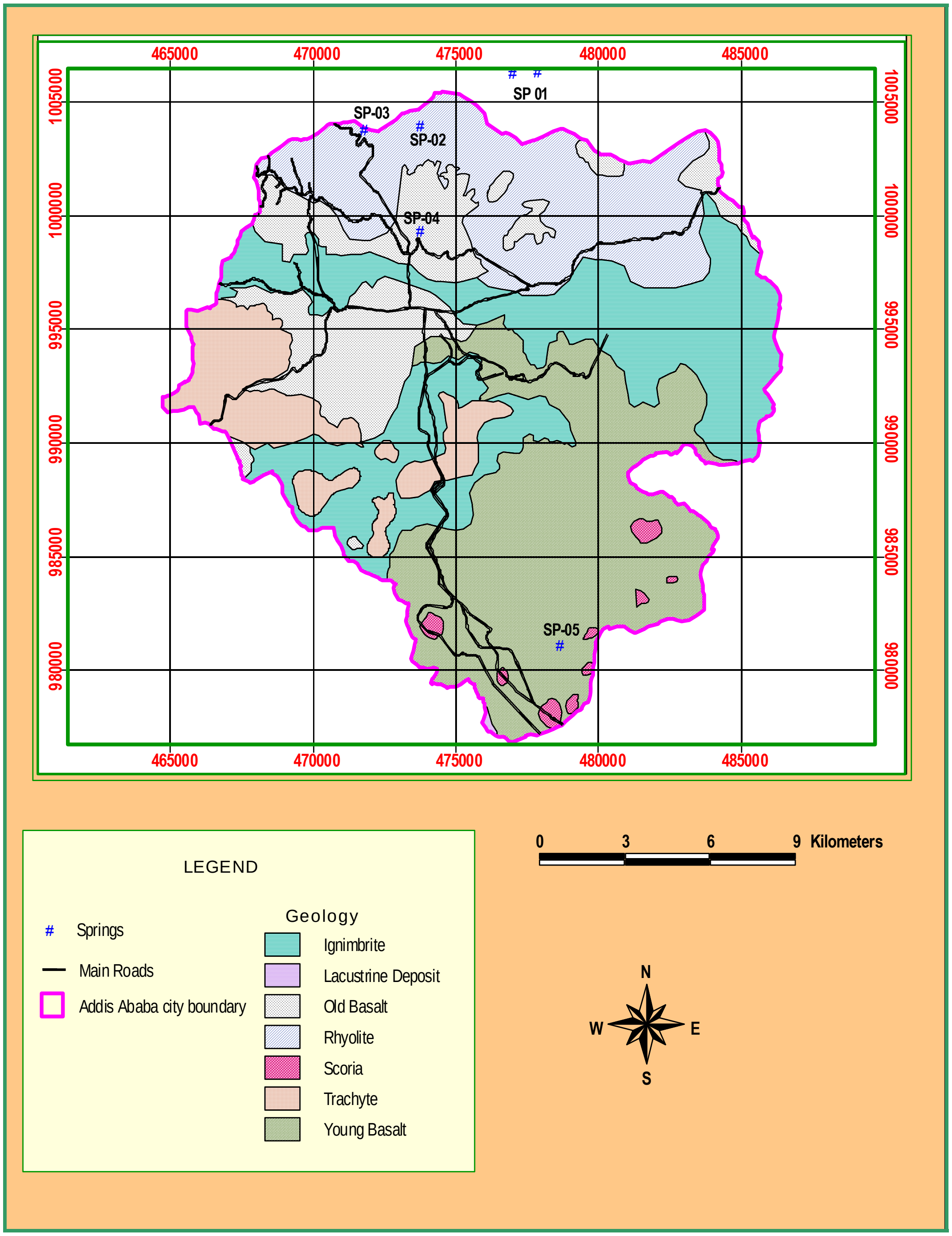

Fig 3-1: General Geological map of Addis Ababa (modified from map produced by AG Consult, Consulting Hydrogeologists and Engineers)

As Addis Ababa is situated at the shoulder of the Main Ethiopian Rift, the above rocks have been subjected to tectonism in the geologic past during the formation of the rift. This is manifested, by a number of fault systems having a general trend of the rift (NE - SW). Although there are some faults and lineaments oriented E-W, N-S and NW – SE, most of them follow the rift trend. The major lineament oriented in NW direction situated to the northeast of the Akaki wellfield, which extends between Akaki and Dukem (following the main Debre Zeit highway) is one of the lineaments, which does not follow the rift trend.

A long fault line running east west via Kessam river, Addis Ababa and Ambo, cut across the western rift escarpment and uplifted its northern block (Zanettin et al., 1978) marking the upper (outer) boundary of the western Ethiopia Rift margin. The Entoto silicics are confined along this fault and form a ridge. The fault has its down thrown side to the south in the Addis Ababa area (Haileselassie Girmay, 1989).

Another prominent normal fault in the city is the Filwuha Fault. This fault has a trend of NE-SW (Kundo, 1958; Morton, 1974; Haileselassie Girmay, 1989). Haileselassie Girmay (1989) found that the fault is not vertical and its throw can be estimated to be about 40m, which is approximately the thickness of the welded glassy ignimbrite. This fault has acted as a dam to the welded glassy ignimbrite, but not to the basalt as it was assumed previously. For this reason there is quite different geology in the south and north parts of the area. Thus, the age of the fault may be bounded by 5.0My (the age of the welded glassy ignimbrite) and 6.4My (the age of plagioclase-phyric basalt).

Kundo (1958) proposed that the hot springs in Filowha are controlled by this fault. The presence of hot springs, south of the fault gives resistivity contrast on the either side of the fault. Joints with different spacing, opening and orientation are also common in the area. The dominant preferred orientation of joints occurring in different rock units is NNE-SSW (Kebede et al., 1990), which is sub parallel with the general trend of rifting. They found joint spacing of 15-200 cm (in most basalts), 5-100 cm (in trachybasalts, trachytes and rhyolites) and 2-100 cm (in ignimbrites).

The density of faults and lineaments increases to the southeast towards the rift valley. Therefore a number of faults and lineaments are concentrated around the Akaki wellfield area. Fig. 3-2 shows a simplified structural map of the area.

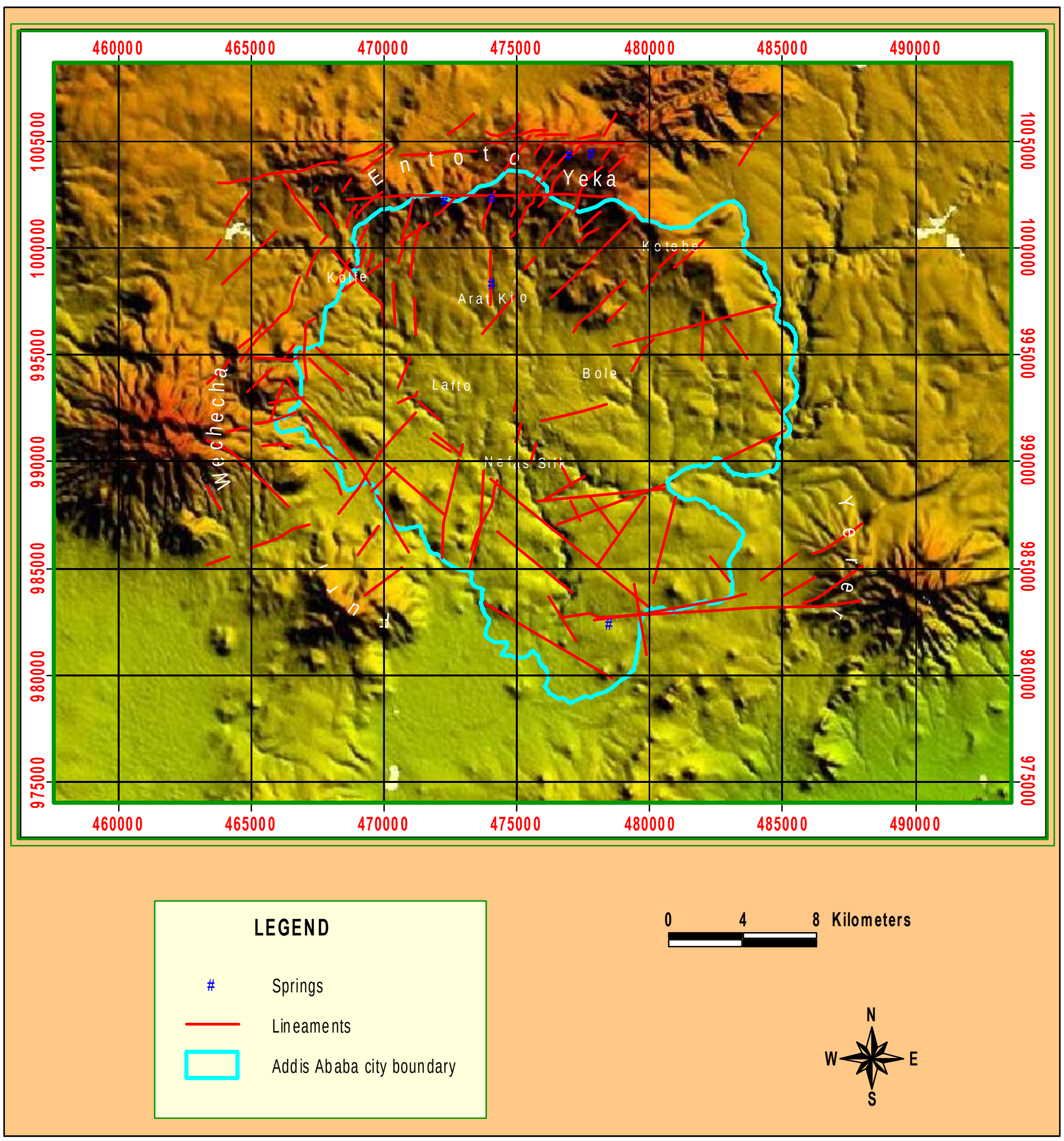

Fig 3-2: Simplified structural map of Addis Ababa

3.3 LOCATION OF SPRINGS AND GEOLOGICAL SET UP

As described earlier, the geology of Addis Ababa is very complex. A number of rock units of different composition and/or age can be encountered along a given transect. As a result, it happens that the springs generally fall in three different geological settings. Three of them (namely Akako, Entoto and Gojam-ber) that are located to the northern part of Addis Ababa lie on the Entoto rhyolites, one of them (Ras Mekonnen spring) on the Addis Ababa basalts and Fanta spring that is located further to the south lies on the young basalts.

Volcanic rocks have a wide range of chemical, mineralogic, structural, and hydraulic properties, due mostly to variations in rock type and the way the rock was ejected and deposited. Unaltered pyroclastic rocks, for example, might have porosity and permeability similar to poorly sorted sediments. Hot pyroclastic material, however, might become welded as it settles, and, thus, be almost impermeable. Silicic lavas tend to be extruded as thick, dense flows, and they have low permeability except where they are fractured. Basaltic lavas tend to be fluid, and, they form thin flows that have considerable pore space at the tops and bottoms of the flows. Numerous basalt flows commonly overlap, and the flows are separated by soil zones or alluvial materials that form permeable zones. Columnar joints that develop in the central parts of basalt flows create passages that allow water to move vertically through the basalt. Basaltic rocks are the most productive aquifers in volcanic rocks.

The volcanic rocks of Addis Ababa are genetically from different sources that gave them textural and compositional differences. Moreover their age difference is responsible for their being subjected to different geological processes (physical, chemical and tectonic) that would tend to alter them. As a result, different geochemical reactions that took place in the different geological media have the chance to yield waters of different chemical composition. Apart from the inherent properties of the original rocks, the degree to which the rocks are altered (related to the age of the rocks) would result in a modified media for the flowing water.

Numerous tectonic structures of local and regional scale are also found in Addis Ababa area. The emergence of the springs is therefore related to the existence of these local fractures and/or regional faults. A North-South cross section crossing two of the springs (Akako and Fanta) shows the existence of a series of step faults (fig 3-3).

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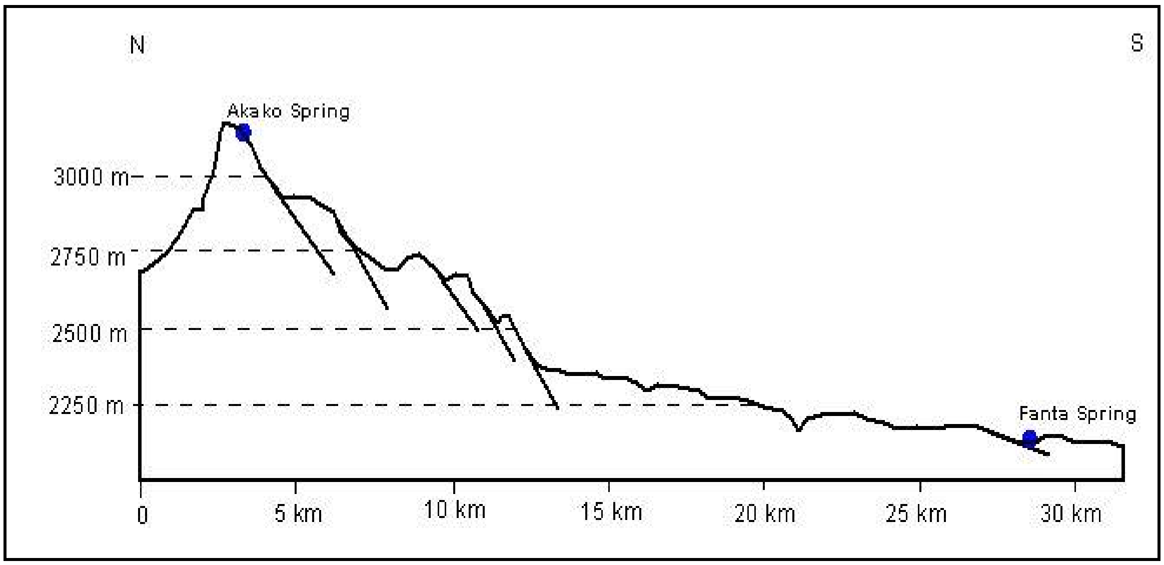


Fig. 3-3: N-S Cross Section (Intoto to Fanta area).

In general, the genesis of the rocks, the geochemical processes that have been taking place, the mineral composition of the rocks and the tectonic history of the area matters the mode of emergence and chemical composition of the springs.

CHAPTER FOUR

HYDRMETEOROLOGY

4.1 GENERAL

The water source of springs can vary. Some springs can be fed by shallow groundwater seepage out of the soil, others are fed by deep aquifer water discharged under artesian pressure. These differences influence the hydrology and water chemistry of springs. However, the water source of most springs is rainfall that seeps into the ground uphill from the spring outlet. The amount, or yield, of available water form springs may vary with the time of the year/s and rainfall. Therefore, the study of springs in a given area demands knowledge of the different hydrological elements that might affect the system. In this chapter hydrological characteristic of the project area will be described with emphasis given to rainfall situations. For this purpose data from four meteorological stations have been used. The names and geographical locations of the stations are as described in Table 4-1 below.

Station Name	Latitude	Longitude	UTM-N	UTM-E
Addis Ababa (Observatory)	9°02 N	38°43 E	998459	468860
Intoto	9°03 N	38°42 E	1000303	467030
Addis Ababa (Bole)	9°02 N	38°45 E	998456	472523
Akaki Besseka (M.S.)	8°58 N	38°57 E	991078	494505

Table 4-1: Location of meteorological stations in Addis Ababa

The selection of the meteorological stations is in such a way that their distribution is in coherence with the distribution of the springs (fig 4-1).

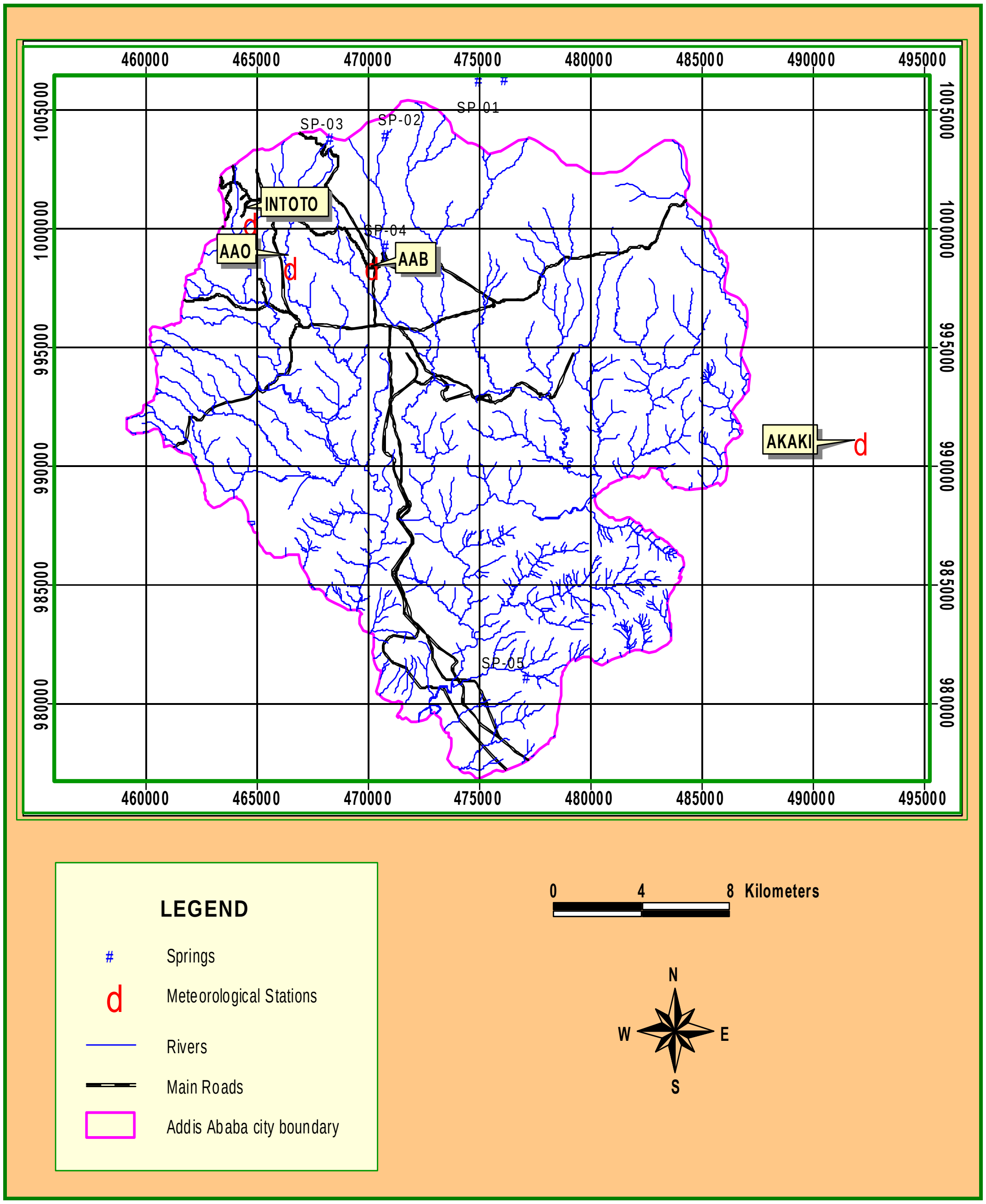


Fig 4-1: Map of meteorological stations in Addis Ababa area

4.2 CLIMATE

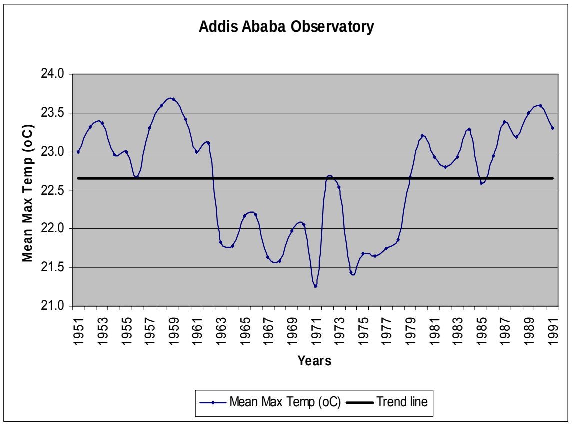
The processes of rock weathering are strongly influenced by temperature and by amount and distribution of precipitation. The influence of climate on water quality goes beyond these direct effects, however. Climatic patterns tend to produce characteristic plant communities and soil types, and the composition of water of streams (which might later percolate to join the groundwater) draining such areas could be thought of as a product of the ecologic balance.

Certain of the major ionic constituents of natural water are influenced more strongly than others by climatic effects. Bicarbonate, for example, tends to predominate in water in areas where vegetation grows abundantly. Some metals are accumulated by vegetation and may reach peak concentrations when plant-decay cycles cause extra amounts of these metals to enter the circulating water.

National Atlas of Ethiopia (1981) defined five climatic zones: "Kur" (Alpine), 3000m and above mean sea level; "Dega" (temperate), 2300m to about 3000m; "Weina Dega" (Sub tropical), 1500 to about 2300m; "Kolla" (Tropical), 800m to about 1500m and "Bereha" (Desert), less than 800m. Having a maximum and minimum elevation range a little above 3000m and a little below 1500m respectively, most part of Addis Ababa falls under the Weina Dega (Sub tropical) category. Accordingly the climate of Addis Ababa area is typically characterized by two distinct seasonal weather patterns: the wet season which extends from June to September, contributing about 70% of the annual rainfall, and the dry season which covers the period from October to May with a minor rainy season in March and April well known for its frequent failure. Such climates which are characterized by alternating wet and dry seasons may favor weathering.

4.3 TEMPERATURE

A changing trend of temperature would imply a changing trend of the extent of evaporation and hence a changing trend of infiltration. According to the National Meteorological Agency data at the Addis Ababa observatory for the past 40 years, a general increasing trend of this element has been observed (fig. 4-2).



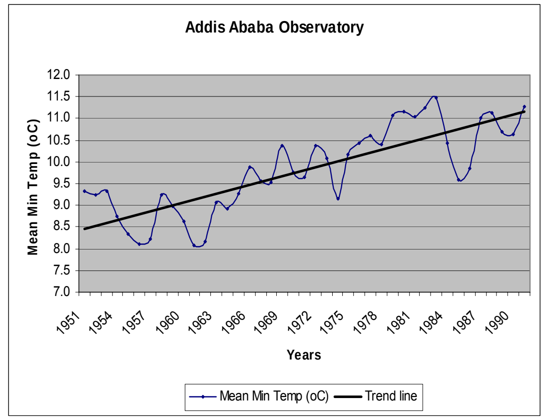


Fig 4-2: Trends of mean maximum (left) and mean minimum (right) temperatures at Addis Ababa observatory since 1951.

Obviously, the impact of this trend on the productivity of spring sources is negative.

4.4 RELATIVE HUMIDITY

The observed data between the years 1951 and 1985 at the Addis Ababa observatory showed a decreasing trend of relative humidity (fig. 4-3) which would result in an increased evaporation. The effect of relative humidity might not be as such important as no open water bodies exist within the boundary of Addis Ababa.

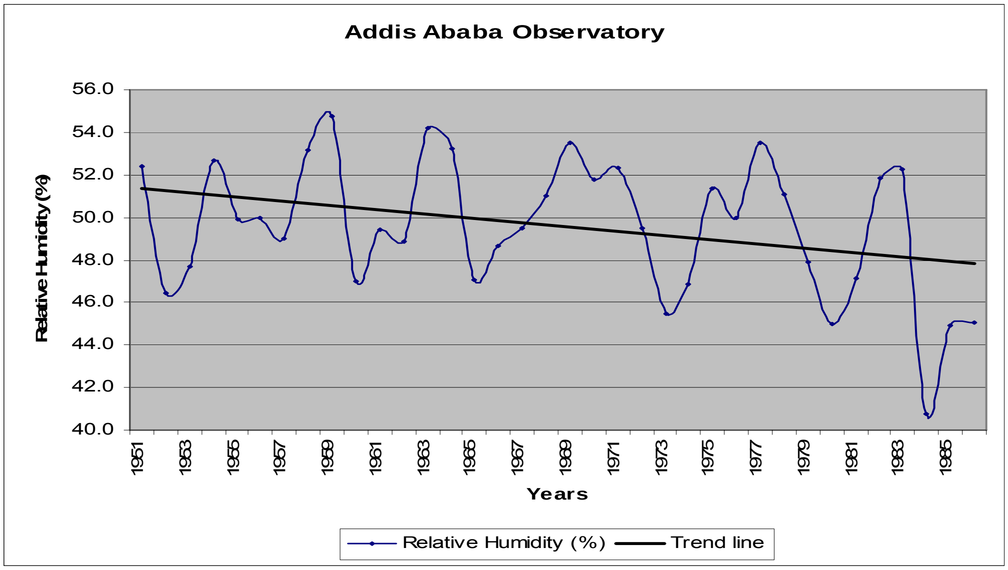


Fig 4-3: Trend of relative humidity at Addis Ababa observatory since 1951

4.5 SUNSHINE HOURS

The longer the duration of sunshine hours, the higher will be the rate of evaporation loss giving rise to a direct relationship between the two. Data trend between the years 1965 and 1985 was also increasing (fig. 4-4) which tend to enhance evaporation and affect groundwater recharge negatively.

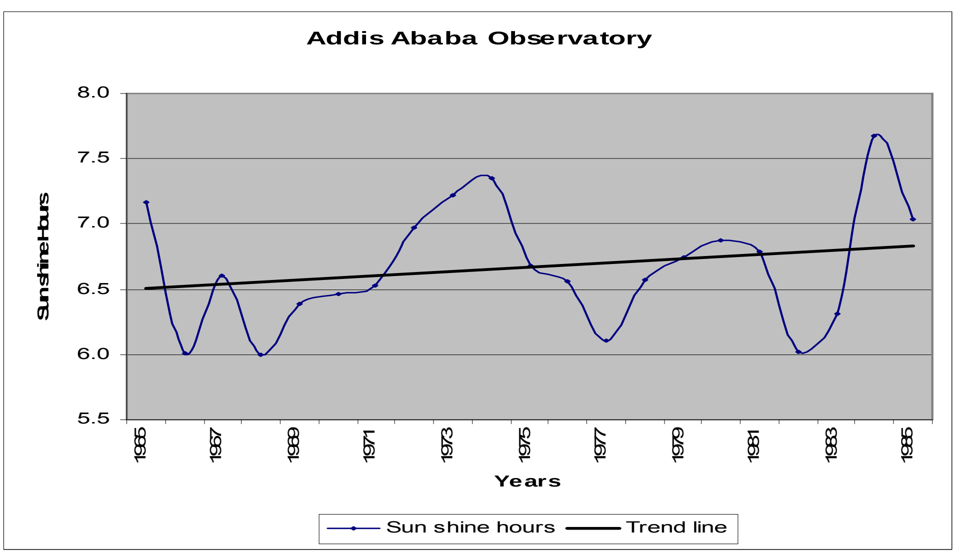


Fig 4-4: Trend of sunshine hours at Addis Ababa observatory since 1951

4.6 PRECIPITATION

Hadwen (1975) stated that there are very few areas in Ethiopia where snow is an important type of precipitation (snow exist on top of mountains), but hailstorms are quite common in the rainy season, especially in areas above 2,000m a.s.l.

According to Daniel (1977) classification of Ethiopia's rainfall regions, Addis Ababa is located in the region where the rainy months are contiguously distributed (Regime IE). In this region there are seven rainy months from March to September and the small rains occur from March to May. The big rains are from June to September. High concentration of rainfall occurs in July and very high concentration in August.

In this study, monthly total rainfall records of four stations for the year between 1964 and 2004 is used to analyze monthly mean rainfall, annual mean rainfall, and rainfall coefficient. The mean monthly and annual mean rainfall of National Meteorological Services Agency (NMSA) stations at Entoto, Addis Ababa Bole, Addis Ababa Observatory (Tekelehaimanot) and Akaki are shown in table 4-2. All stations are located at different geographical coordinates. Hence, the discharge variability of each spring will be compared with the rainfall variability of the closest station to see how rainfall affects spring flow.

Station Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Mean Annual RF (mm)
Intoto (mm)	15.6	38.3	61.0	87.3	61.8	140.0	306.9	322.5	145.4	27.2	9.9	9.8	1225.7
Addis Ababa Obs. (mm)	19.0	45.0	73.0	95.1	83.7	138.1	267.9	292.8	183.9	38.9	8.6	10.1	1256.1
Bole (mm)	15.6	36.3	68.0	88.7	78.1	120.0	237.8	238.3	137.6	33.3	5.6	5.2	1064.5
Akaki (mm)	14.3	40.6	63.0	95.1	66.2	129.3	272.1	295.2	142.7	23.7	4.6	3.6	1150.4

Table 4-2: Mean monthly rainfall at four stations

The monthly mean rainfall records for forty years showed that the mean annual rainfall at Entoto station (at an elevation of 2900m a.s.l), Addis Ababa Observatory (at an elevation of 2408m a.s.l.) Bole (at an elevation of 2324m a.s.l.), and Akaki Mission (at an elevation of 2170m a.s.l.) are 1088.5mm, 1251.5mm 1164mm and 1087.01mm respectively. Thus, the city receives annual average rainfall of about 1123mm and the long term mean annual rainfall observed at Addis Ababa Observatory is about 1256mm.

Moreover, in all stations the heaviest amounts of rainfall occur in the months of August. While the minimum amount of rainfall occurs in November at Addis Ababa observatory and in December at all other stations. The above data also reveal that in the Akaki river basin more than 70% of the total amount of rainfall occurs in the months of June, July, August and September.

The relationship between the rainfall and the different stations showed that the spatial distribution of rainfall is predominantly affected by altitude. Generally, the annual rainfall value is observed to increase with elevation as shown in fig. 4-5. The local variation in rainfall amount can be attributed to the location of the stations with respect to the local physiographic physiographic conditions. As a result meteorological stations at closer proximity to mountainous areas (Entoto, Addis Ababa and Akaki) might have higher rainfall records than those away from elevated areas (Bole). Another possibility is the difference in the type and installation differences of raingauges.

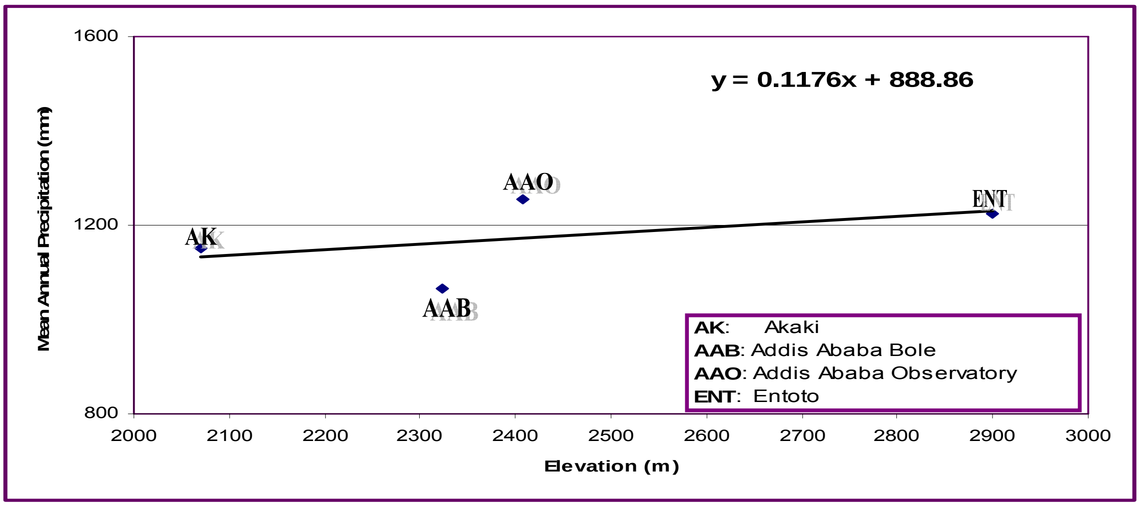


Fig 4-5: *Variation of annual precipitation with elevation*

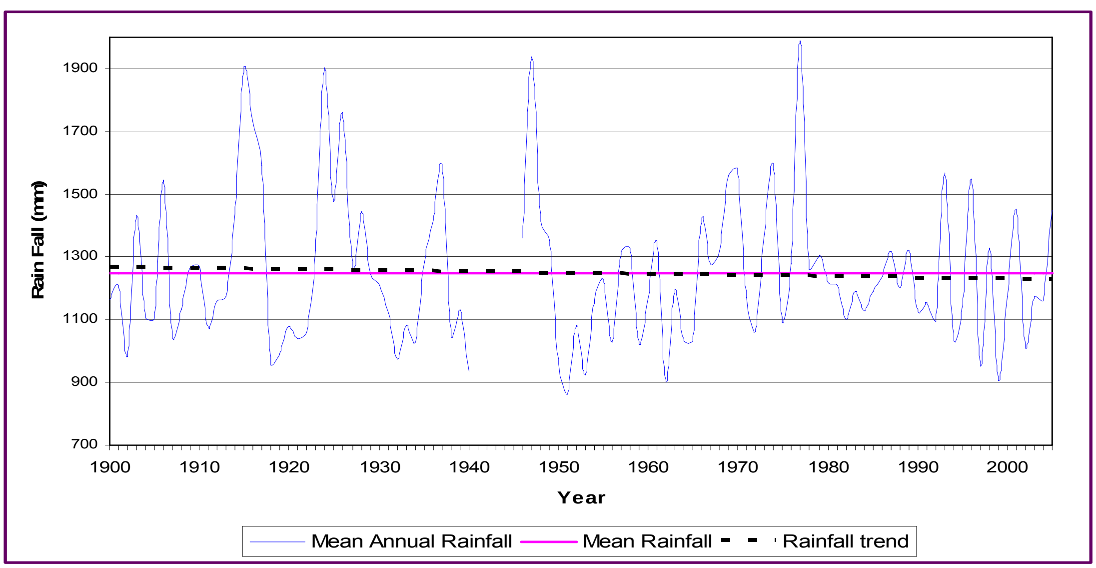


Fig 4-6: *Rainfall trend at Addis Ababa Observatory since 1900.*

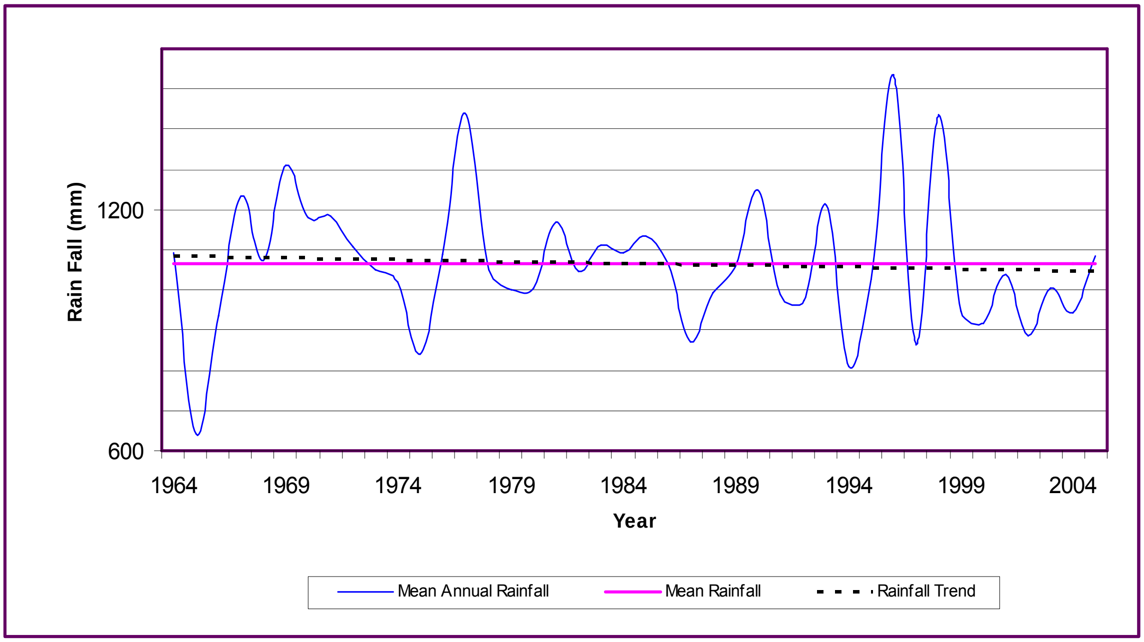


Fig 4-7: *Rainfall trend at Bole Observatory since 1964*

As can be observed from the rainfall trend at the Addis Ababa and Bole (Addis Ababa) observatories for the years 1900 to 2005 and 1964 to 2004 respectively, follows a decreasing trend in both cases. Consequently, the trend falls below the mean rainfall for the observed years at both stations. This trend seems to continue as the mean annual temperature and sunshine hours are following an increasing trend. This may affect the regimen of the springs in the future.

As it was shown earlier above in Table 4-2, the precipitation occurs through out the years but it shows variation in amount from season to season. To distinguish between “rainy" months and “dry months", it is necessary to calculate the rainfall coefficient (RC) of each months in all station. The rainfall coefficient (which is the ratio between the mean monthly rainfall and one twelfth of the annual mean) of each month in the respective stations is presented in table 4-3.

Station Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Intoto	0.15	0.37	0.60	0.85	0.61	1.37	3.00	3.16	1.42	0.27	0.10	0.10
Addis Ababa Obs.	0.18	0.43	0.70	0.91	0.80	1.32	2.56	2.80	1.76	0.37	0.08	0.10
Bole	0.18	0.41	0.77	1.00	0.88	1.35	2.68	2.69	1.55	0.38	0.06	0.06
Akaki	0.15	0.42	0.66	0.99	0.69	1.35	2.84	3.08	1.49	0.25	0.05	0.04

Table 4-3: Rainfall coefficients

A month is distinguished as rainy when the corresponding monthly rainfall coefficient reaches 0.6 Where as dry month has less than 0.6 rainfall coefficient. Daniel (1977) classified rainy months of Ethiopia into small rains (0.6 to 0.9) and big rains (1.0 and over). The big rainy months are further classified into three groups: Moderate concentration (1.0 to 1.9), high concentration (2.0 to 2.9) and very high concentration of rainfall (3.0 and above).

As it is shown above, there are seven rainy months from March to September and five dry months from October to February. The small rain occurs from March to May in Entoto, Addis Ababa Observatory and Akaki, while in Addis Ababa Bole it occurs in March and May. The big rain is from June to September in Addis Ababa Observatory, Bole and Akaki, with moderate concentration in June and September. However in Intoto, the big rain is from June to August. July and August are characterized by high concentration of rainfall in all stations. In general, the computed results show great similarity with Daniel's (1977) classification of the Ethiopian rainfall regions.

CHAPTER FIVE

HYDROGEOLOGY

5.1 GENERAL

The origin, flow and chemical constitution of groundwater is controlled by the type of lithology, distribution, thickness and structure of hydrogeological units through which it moves (UNESCO, 1972). Moreover, the stresses due to tectonism and weathering conditions govern the hydrogeochemical characteristics of earth materials. Therefore, acquiring knowledge about the existing aquifer materials, their spatial distribution and their hydraulic properties is a necessity.

The whole terrain on which the study area falls are volcanic rocks mainly basalts, rhyolites, trachytes, scoria, trachy-basalts, ignimbrites, welded and unwelded tuffs. Yet, groundwater circulation and storage in volcanic rocks depend on the type of porosity and permeability formed during and after the rock formation. The primary and/or secondary porosity developed in the different rock formations is different according to their genesis, the weathering and tectonic conditions they were subjected to. Rocks possessing a primary porosity may not necessarily give rise to primary permeability unless the primary porosities are interconnected. Later connection of primary porosities by means of weathering or fracturing may result in secondary permeability.

In volcanic rocks the porosity available for groundwater flow is often much less than the total porosity, especially in fresh (young) volcanics. Specific yield (drainable porosity) is small for fine grained pyroclastic formations, ashes and weathered rocks. Wherever the mentioned volcanic rocks possess primary and/or secondary porosities, they serve as major groundwater supply aquifers for large parts of Addis Ababa.

Common porosity values of volcanic formations are given in table 5-1 (the ranges are only indicative and values are derived from a wide literature review). According to this table the drainable porosity of the old Entoto rhyolites will be much less than 0.5-5% while the young basaltic formations of Southern Addis would be in the order of 2-8%.

Table 5-1: Common porosity values of volcanic formations (source: Ground Water Studies, International Guide for Hydrogeological Investigations, edited by-V.S.Koalevsky, G.P Kruseman, K.R Rushton).

Material	Total Porosity (%)	Drainable Porosity (%)	Comments
Basalt flows	0.8 – 20	0.1 – 8	Dense to highly vacuolar
Basaltic interflows	20 – 50	5 – 15	Breccia at the top and bottom of a lava flow
Basaltic formations	5 – 40	2 – 8	Increases with content of scoria and pyroclasts
Basalt sheets (traps)	4 – 10	<1 – 2	Several flows, no pyroclasts, moderately old
'Core' basalts	2 – 5	<0.1 – 4	Thermally altered and dyke-intruded
Conglomerates	2 – 25	1 – 4	Mostly basaltic
Loose pyroclasts	25 – 50	5 – 10	Fresh lapilli and blocks
Ash fall	25 – 40	1 – 5	Relatively fresh
Phonolites	2 – 4	1 – 6	Dense flows
Phonolitic ignimbrites	20 – 60	0.5 – 8	Dense to poorly welded tuff
Pumices	50 – 85	<0.1 – 1	Non-connected pores, unfractured
Obsidians	~0.5	<0.1	Not a formation
Rhyolites	0.1 – 30	0.5 – 5	Dense to vacuolar
Rhyolitic ignimbrites	15 – 70	0.5 – 10	Dense to poorly welted tuff
Rhyolitic interflows	30 – 70	1 – 5	Breccia at the bottom of a lava flow
Lahars (mudflows)	20 – 35	<0.5	Heterometric, variably consolidated
Volcanic soils	40 – 60	<1 – 5	Variable

Note: Total porosity and drainable porosity decreases with age.

In general, Tamiru Alemayehu et.al. 2005 has indicated that main aquifers in and around Addis Ababa are categorized in to three groups:

- Shallow Aquifers: made of weathered volcanic rocks and alluvial sediments along river courses.

- Deep Aquifers: made of fractured volcanic rocks that tap fresh groundwater.
- Thermal Aquifers: that are located at depths greater than 300m.

5.2 POROSITY

As explained earlier the variable and complex lithology and hence aquifers of varying porosity in the area makes the observed transmissivity extremely variable. So as to understand the degree of variation, a brief explanation with respect to the hydraulic properties of the different lithologies is given below.

BASALTIC LAVA FLOWS

The texture of basaltic lava flows in the study area varies from porphyritic (olivine and plagioclase) to aphanitic. Basically, high water storage and transmitting capacity of basaltic lava flows is due to joints caused by cooling, lava tubes, vesicles that are interconnected, tree moulds, fractures caused by buckling of partly congealed lava (aa lava surface) and voids left between successive flows. Old porphyritic basaltic lava flows dominantly cover the slopes of Entoto, central and western parts of Addis Ababa. It's water circulation and storage capacity is dependent on the degree of weathering and fractures. Accordingly, the hydraulic properties of these rocks have been modified by these systems of faults and fractures.

Depending on the degree of weathering and the resulting weathering zones the porphyritic basalts show difference in water infiltration properties. In some localities, like the area around Kidane Mehrat Church (east of Shiro Meda), the secondary permeability of porphyritic basalts is due to deep weathering zones (Tamiru Alemayehu, et.al, 2005). Besides large concentrations of weathering fractures that have different orientation and opening increases the overall water transmitting properties of the rock body. Usually the greatest permeability is found within the partly decomposed weathering zone.

On the other hand, the degree of weathering and associated fractures is less developed in the lava flows that outcrop in the central and western part of the study area. Although there is thick soil cover in some places (e.g. Shegole Meda) the zone of partly decomposed parent materials below the soil horizon is small in thickness (Tamiru Alemayehu, et.al, 2005). Thus, the permeability of porphyritic basalts in these localities is less as compared to the same rock outcrop in the north eastern areas.

The young porphyritic basalt that outcrops in the southern parts of Addis Ababa varies from massive to fractured type. It is fresh to slightly weathered. The fractured variety is the most permeable and productive aquifer in Akaki area (Anteneh Girma, 1994). Outcrop of this rock varies texturally from massive to vesicular type. Vesicles, which are abundant on the aphanitic basalts, are not interconnected and in some cases partially filled by secondary minerals. Thus, vesicles have little or no effect on the overall rock permeability. However, in some localities (e.g. near Bole Air Port) vesicles are interconnected due to weathering fractures and/or tectonic discontinuity. Consequently, the water transmitting capacity of vesicular basalts increases to some extent.

In the massive aphanitic basalts the presence of vertical and horizontal fractures significantly increases the water circulation and storage capacity of the rocks. However, the same rock exposed at different localities may show differences in hydraulic their properties depending on the spacing (density), aperture (opening size), interconnection and orientation of the fractures.

Measurements taken from different places show that there is variation in the spacing of vertical fractures form about 0.3 to 1 meter and horizontal fractures from about 1.5 to 2 meters. Likewise, the aperture in the vertical and horizontal fractures varies from about 10 to 30 mm and 10 to 20 mm respectively. Moreover, there are also inclined fractures that run in different directions.

The other difference in water transmitting capacity is related to the extent to which the aphanitic basalts are affected by weathering. The permeability becomes high in area where this basalt is intensively intersected by weathering fractures. In the southwestern Addis Ababa, near ALERT, for example the aphanitic basalt is highly weathered and affected by horizontal and inclined local weathering fractures. The spacing in the horizontal fractures varies from about 3 to 5 cm and the aperture reached up to about 2 cm (Tamiru Alemayehu, et.al, 2005). In some localities, the basaltic lava flow is slightly weathered and consequently, posses law infiltration capacity.

WELDED TUFF

This rock unit is widely distributed in the northern, central eastern and south western parts of Addis Ababa. The strongly welded tuff is exposed in the central and western parts. While, young welded tuff varieties cover extensive areas in the central and southern parts of Addis Ababa. According to Davis (1966) welded tuffs have medium to low primary porosity and very low permeability. Thus the water circulation and storage capacity of welded tuff depends on the secondary porosity and permeability developed through fracturing and weathering processes. In the study area, the degree of weathering and fracturing of these rocks varies from place to place. In most places the welded tuffs are fresh to slightly weathered. In the flat-laying areas of southern and southeastern parts of Addis Ababa as well as along most river valleys the welded tuff are deeply weathered and covered by soils having different thickness.

The secondary fractures, that are mainly the results of weathering and tectonic activity, affected the ignimbrite in different manner. In some localities the welded tuff is massive, slightly weathered and fractures are scarce or absent. Thus, the secondary processes have very small contribution in the overall water circulation and storage capacity of welded tuff. On the contrary, there are places where block fractures divided the massive welded tuff into rectangular blocks. Mostly these fractures are open to a considerable depth and transmit large quantities of water. On average the spacing and aperture of vertical fractures in ignimbrite varies from about 0.5 to 2 meter and 2 to 4 cm respectively. Likewise, the horizontal fractures vary from about 1 to 4 meters in spacing and 1 to 3 cm in fracture opening (Tamiru Alemayehu, et.al, 2005).

Therefore, in most localities welded tuff developed good secondary permeability largely from open fractures and to some extent from weathering zone. When there is high degree of fracturing and weathering, welded tuffs have the capacity to hold water and become a productive aquifer.

SILILIC LAVA FLOWS AND DOMES

The rhyolitic and trachytic lava flows are mostly considered as impervious rocks. The water storage and transmitting capacity is thus largely dependent upon secondary porosity and permeability.

Rhyolitic lava flows are found dominantly along the slopes and foothills of Entoto ridge. The secondary porosity in rhyolite is due to weathering and associated fractures. In the western parts of Addis Ababa weathering deeply affected the rhyolite that has formed the gentle slopes of Entoto producing soils of thickness as greater than 10 meter. Moreover, weathering fractures locally increases the porosity of the rhyolitic lava flows. In some localities vertical fractures having about 0.5 to 1 meter spacing and about 10 to 20 mm opening intersect the rocks. Thus, the weathering fractures and weathering zone significantly modify the limited primary porosity and permeability of rhyolitic lava flows. On the other hand, the rhyolitic lava flows outcrop in eastern parts of Entoto ridges is slightly weathered and less fractured. Consequently, there is poor soil development particularly on the slope and top parts of the ridge. Rock fragments are dominantly covering this part. Relatively shallow soil profile constitutes the gentle slope and foothills of the ridge. Therefore, in some place where the rhyolitic lava flows are intensively weathered and highly fractured, infiltrated water through fractures feed the aquifers that lie on flat-laying areas. Where there are massive and slightly weathered parts of this rock unit, most of the precipitated water is readily lost as runoff.

Trachytic domes have steeper slopes, hence there is thin or no soil formation. Therefore, the water that precipitated on the trachytic domes of Mt. Wechecha, Mt. Furi and Mt. Yerer are mostly lost as runoff rather than vertical infiltration. The trachytic lava flows cover the foothills and moderately dipping topography of the southern and southwestern parts of Addis Ababa. Due to the existing thick black cotton soil cover, outcrops are scarce. This rock unit is slightly to moderately weathered and intersected by fractures. The major vertical fractures on the trachytic lava flow have spacing of about 0.5 to 1 meter and the opening in this fracture varies from about 2 to 3 cm. Likewise, local vertical fractures that have about 5 to 20 cm fracture spacing and up to 5 mm fracture opening are also observed in the same outcrop (Tamiru Alemayehu, et.al, 2005). The occurrence of major tectonic displacement and deep weathering zone in trachytic lava flows strongly changes the hydraulic characteristics of the rock. On the other hand, minor fractures have local permeability effect. However, an intensively weathered and fractured trachytic lava flow under favorable conditions develops not only water transmitting but also water holding properties.

The trachy-basalts are exposed in the western parts of Addis Ababa, around Repi and General Wingate School (Tamiru Alemayehu, et.al, 2005). They are slightly weathered and intersected by fractures. The fractures are dominantly inclined and fracture spacing varies from about 20 to 40 cm. Although the spacing of fractures in trachy-basalts is small compared to other rock type, due to the tight fracture openings the resulting water infiltration capacity is minimum. Due to slight weathering there is thin soil cover on trachy-basalts.

INTERGRANULAR POROSITY

Intergranular porosity in the study area is mainly associated with the volcanic activity and/or weathering and erosion processes. Alluvial sediments are deposited in the southern parts of Addis. It is a loose material consisting of clay, silt, sand and gravel in different proportions. In a vertical succession the deposits have coarse material (gravel) at the bottom of the channel and fine materials (silt & clay) at the top. Mostly the alluvial deposits are localized in the narrow channel and terraces of the valleys. The thickness of alluvium deposits varies from place to place depending on the topographic variation in the area.

As it was observed from lithologic logs of boreholes, alluvium deposits are encountered interbeded with different lava flows, pyroclastic materials and paleosols at different depths. Alluvial deposits often occur in flat-laying topography where the area is swampy or waterlogged. The thickness of alluvium that covers swampy area of Filowha, for example, varies from 2 to 4 meters (Tamiru Alemayehu, et.al, 2005). The primary porosity and permeability in alluvial sediments result from voids between the grains. The magnitude in turn depends on the size, shape, sorting and packing of grains. The alluvial sediments in Addis Ababa are poorly sorted, highly porous and permeable. Thus under favorable conditions they may store appreciable amount of water and characterized by high water infiltration capacity.

Although very localized, colluvial deposits having high porosity and permeability occur in the foothills of Entoto ridge, Mt. Wochacha, Mt. Furi, Mt. Yerer and other elevated areas (Tamiru Alemayehu, et.al, 2005). Loose pyroclastic materials derived from different volcanic centers make up intergranular porosity. The most important characteristic features governing the groundwater movement and accumulation in unconsolidated pyroclastic materials are related to fragment size, sorting and degree of cementation. Loose pyroclastic material includes ash and agglomerates. At depth these materials are found to be interbeded with alluvial sediments, paleosols and lava flows. Volcanic ashes and agglomerates have high water holding and transmitting capacity. On the contrary, tuff has low permeability, but the secondary processes specifically weathering increases significantly the water infiltration capacity of tuff.

In boreholes drilled at Building College (Lideta) and Sunsuzi 16m and 18m thick clay soil horizons have been encountered respectively (Tamiru Alemayehu, et.al, 2005). The black cotton soils in the south have a swelling and shrinkage properties. In the dry season cracks that have different aperture and lateral extent commonly observed. The infiltration capacity of black cotton soil thus become high in the beginning of the rainy season and reduces when the amount of precipitation increase. As a consequence the black cotton soil become saturated and acts as impervious materials.

The two major faults i.e. east west running fault at Entoto and NE-SW oriented Filowha fault changes the topography of Addis Ababa and it's surrounding significantly. The occurrence of many springs at the foot of the former and thermal water along the latter is indicates conducive nature of these faults. Moreover, during faulting associated fractures and fissures developed on different lithologies modify the hydrogeological characteristics of the rock units affected by the fault. Besides, hydrothermal activity might exist associated with faults and volcanic centers. Hydrothermal activity is the expulsion of hot water-rich fluids returning to the surface after having been heated by hot rock or magma at depth. Ground water seeping down into the crust is heated and rises back to the surface through fissures and cracks. As a result hydrothermal alteration of the rocks will dissolve minerals giving rise to the development of pores or a highly weathered material that substantially modifies the original hydrogeological property of the rocks. Ignimbrites and rhyolites of the Filwoha and Entoto area could have experienced this phenomenon.

5.3 TRANSMISSIVITY

Addis Ababa area is underlain by complex system of aquifers of various size and hydraulic properties, which are mostly hydraulically connected. Aquifers can be made up of weathered and fractured volcanic rocks and pyroclastic deposits such as ignimbrites, scoria, tuffs and ashes. Inter-volcanic alluvial deposits and soils also exist as a result of time gaps between successive volcanic eruptions. Volcanic deposits originated from different sources have varying aerial extent and composition giving rise to a complex geological setup. As a result of this complexity, complex aquifer systems have been developed with extremely variable tranmissivity values. A big variation among wells yields can therefore be attributed to this heterogeneity in the transmissivity of the water bearing geological formations.

The aquifer to the north of the Akaki well field mainly covering the Addis Ababa city and in the mountain area consists weathered and fractured volcanic rock with minor sediments deposited between different series of lava flows. Some superficial deposits along the major river courses make shallow aquifers.

According to BCEOM/SURECA, 2000 study, there is a gradual increase in aquifer transmissivity towards the the Akaki wellfield (South Addis Ababa). The Northern portion of Akaki well field that lies within the Addis Ababa city boundary contains a mixture of alluvial and lacustrine materials such as sands, clays, gravels, volcanic ash and tuffs at different depths. Lithological unit made up of black cotton soil and lacustrine clays make the uppermost part of the well field, which in its northernmost portion also includes a considerable thickness of olivine basalt. The basalt is in general thick and includes some scoriaceous basalt and scoria. Tahal and Shawel (1992) suggested the presence of a geohydrologic barrier separating northeast of the well field the current well field area. In general the thickest scoria deposits are located in north-eastern part of the well field at the Akaki town water supply wells (named as EP wells). Although the thickness of the scoria in the well field is highly variable, all the drilled wells have high yields suggesting that the scoria and the basalt (usually reported to be found interbedded) at the well field are equally important as an aquifer. Therefore, the aquifer can be assumed to be made up of mainly weathered and fractured volcanic rocks and pyrolastic deposits such as scoria, fractured scoriaceous and vesicular basalts, ignimbrites, tuffs and ashes (AAWSA et al., 2000).

The calculated transmissivity values for the different parts of Addis Ababa is summarized in table 5-2 below.

Areas	Transmissivity (m^2/sec)		Transmissivity (m^2/day)	
	min	max	min	max
North	3.01E-06	1.26E-02	0.26	1092
West	1.15 E-04	1.1 E-03	9.9	95
East	4.6 E-02	9.20E-05	4	8
Central A.A.	3.01E-06	0.067	0.26	5760
Akaki & Kality	3.19E-05	7.06E-02	2.76	6099
Akaki wellfield	2.12 E-02	1.22	1834	105,408

Table 5-2: Summary of Transmissivity values (AAWSA et al, 2000)

5.4 GROUNDWATER FLOW

The elevation of water level in boreholes can be used to determine the general direction of groundwater flow, with emphasis given to the complexity of the aquifer system in the area. A previous report (AAWSA and Seureca, 1991) had identified regional groundwater flow direction which is assumed to be north - south from Addis Ababa towards the Akaki well field. AGRA (1998) assumed groundwater flow direction in the well field is from the NE towards the SW.

Using much more regional data, AAWSA et al. (2000) indicated that the main groundwater movement is from north to south in the central and northern part of the Akaki river catchment and towards the Southeast direction in the lower part of the catchment (fig. 5-1). In general the groundwater movement is sub parallel to the surface water flow direction and more or less controlled by the topography of the area (fig. 5-2).

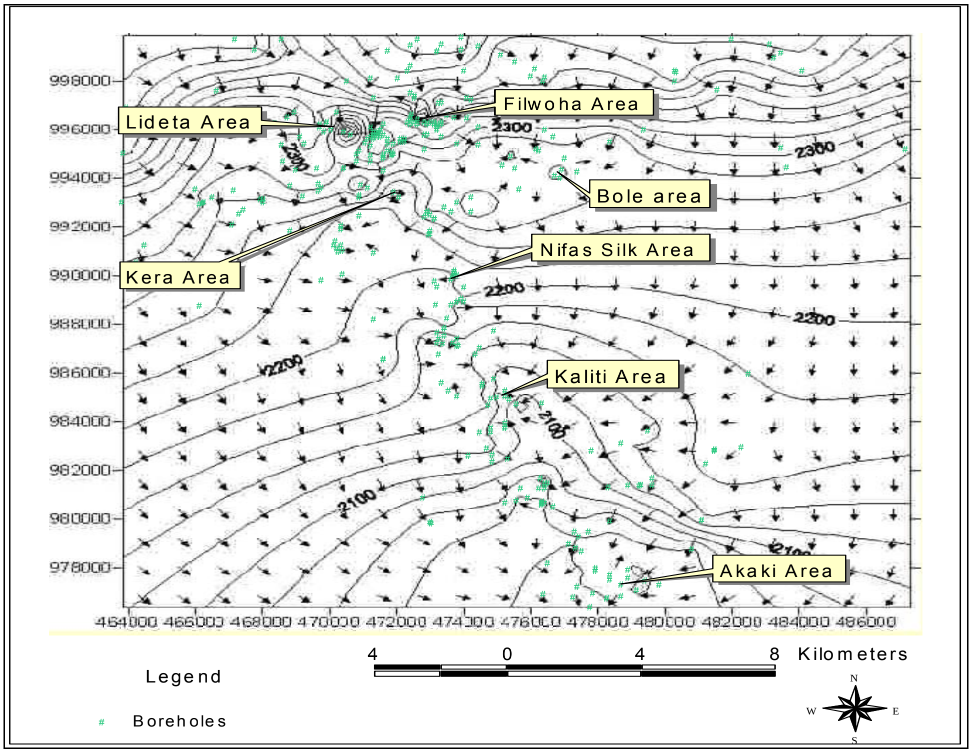


Fig. 5-1: *A 2-D representation of groundwater flow direction*

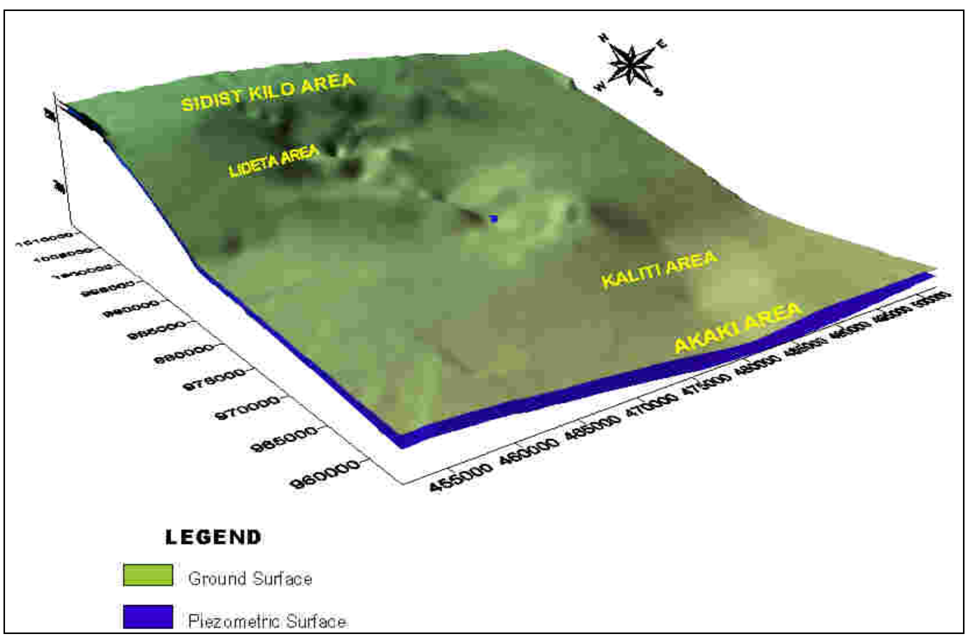


Fig. 5-2: *A 3-D representation of groundwater surface and ground surface*

As far as the groundwater-surfacewater interaction is concerned, the potentiometer surface indicates that the shallow groundwater is in connection with the surface water mainly with Big and Small Akaki river to the north of the Akaki Bridge (Tamiru Alemayehu, et.al, 2005). The base flow in these rivers is mainly contributed from the groundwater. In low areas (small corridor in the city center and East of Kality) the potentiometeric surface is above the ground level and the wells are artesian. The groundwater flow is also supported by pH and EC maps given in figures 5:3 & 5:4 respectively. As can be observed from the figures there is a general increase in both parameters along the groundwater flow direction except for some local variations that may arise from local recharge from rainfall (Akaki area) and pollution (Kaliti area).

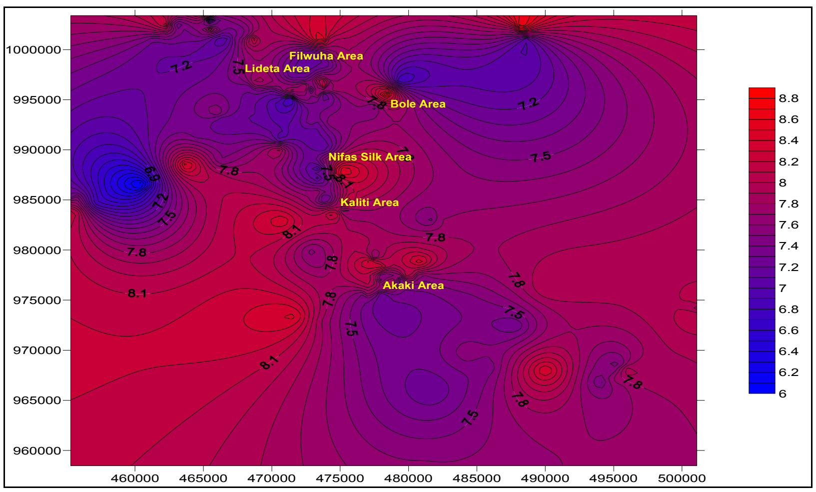


Fig. 5-3: *pH map from Addis Ababa boreholes data*

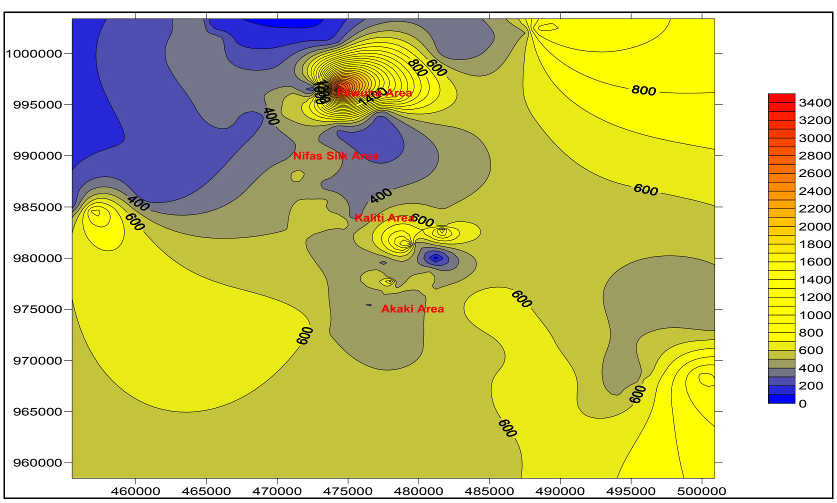


Fig. 5-4: *TDS map from Addis Ababa boreholes data*

CHAPTER SIX

HYDROCHEMISTRY

6.1 GENERAL

An igneous rock terrain contains appreciable amounts of quartz and aluminosilicate minerals such as feldspars and micas. These minerals are originally formed at temperatures and pressures far above those occurring at or near the earth's surface. Therefore, at or near surface environments, these minerals are thermodynamically unstable and tend to dissolve when come in contact with water. The dissolution process causes the water to acquire dissolved constituents and the rock to become altered mineralogically. The dissolution of feldspars, micas and other silicate minerals is strongly influenced by the chemically aggressive nature of water caused by dissolved CO_2. When CO_2 charged waters that are low in dissolved solids encounter silicate minerals high in cations, aluminium and silica, cations and silica are leached leaving an aluminosilicate residue with increased Al/Si ratio. This residue is usually a clay mineral such as kaolinite, illite or montmorillonite. The cations released to the water are normally Na^+, K^+, Mg^{2+} and Ca^{2+}. Another consequence of this process of dissolution is a rise in pH and in HCO_3^- concentration.

6.2 pH, TDS and EC

The pH of natural water is a useful index of the status of equilibrium reactions in which the water participates.

Water sample analysis results have shown that a pH range of 6.7 to 8.3 for Akako and Fanta springs respectively which is normal for groundwater. EC and TDS of the collected samples have also shown a linear relationship as should be expected (fig 6-1).

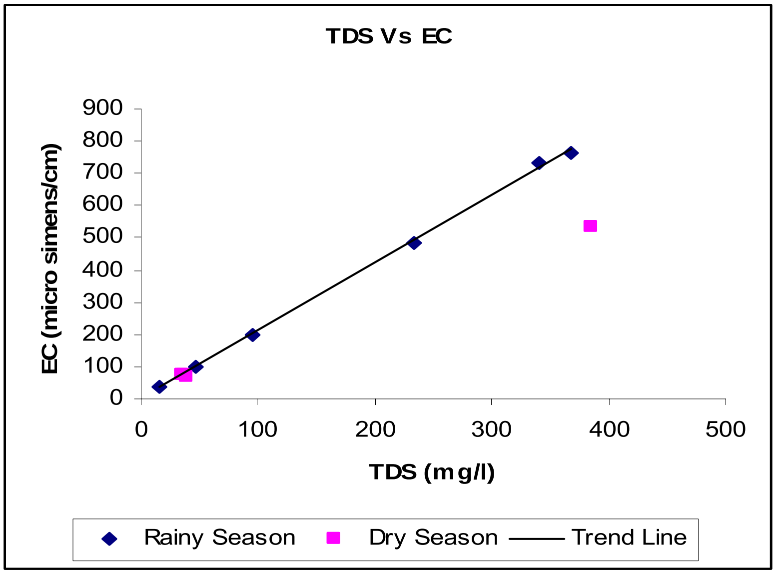


Fig. 6-1: *TDS Vs EC relationships of collected water samples*

6.3 MAJOR IONS

Water Chemistry data has been collected from previous studies for the purpose of analysis and interpretation based on major cations and anions. Accordingly, compiled data from previous studies by Tamiru Alemayehu (2001), AAWSA et.al (2000) and Berhanu Gizaw (2002), is presented in table 6-1 and the resulting piper plot is shown in fig 6-2.

Item	Unit	Akako Spring (A)	Akako Spring (B)	Gojam Ber Spring	Ras Mekonnen Spring	Fanta Spring (A)	Fanta Spring (B)
Ca^{++}	Mg/l	3.24	2.56	7.56	100	55.6	40.8
Mg^{++}	Mg/l	0.68	0.63	2	60	24.1	23.9
Na^{+}	Mg/l	4.3	2.22	8.5	38	34.0	35
K^{+}	Mg/l	2.3	1.81	1.8	3	2.85	4.48
HCO_3^{-}	Mg/l	24	17	4.6	61.02	323.3	351

Cl^-	Mg/l	0.58	0.62	0.9	56.5	10.4	5.69
SO_4^{--}	Mg/l	0.41	0.43	0.72	19	19.9	13.14
NO_3^-	Mg/l	4.85	4.83	3.76	481.41	13.9	14.96
NO_2^-	Mg/l	<0.01	<0.01	<0.01	0.033	1.01	<0.01
F^-	Mg/l	<0.1	<1	0.1	-	<0.1	0.4
SiO_2 (aq)	Mg/l				69.9	38.0	

Table 6-1: *Major ion concentrations of spring water samples.*

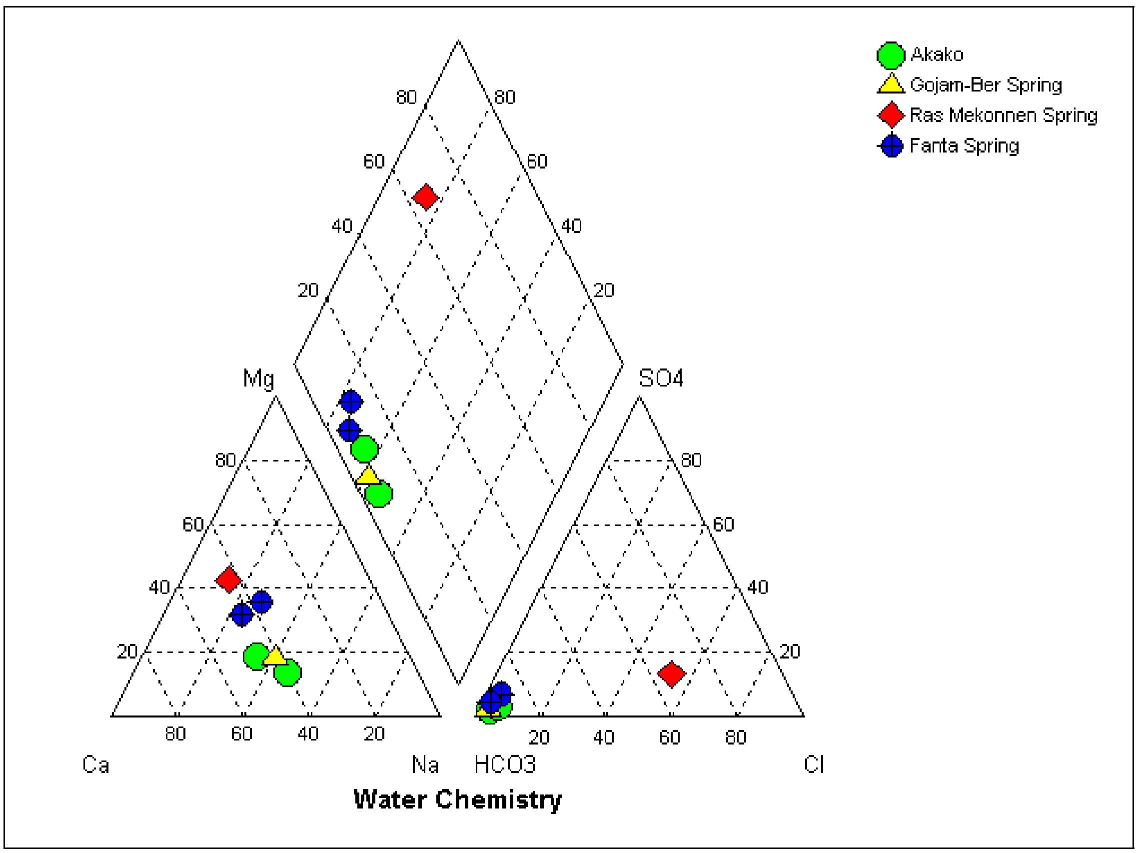


Fig. 6-2: *Piper diagram for major ions (previous data)*

Springs of northern Addis Ababa (Akako and Gojam-Ber) tend to have a relatively high concentration of Na than Ca and Mg. Where central and southern area springs tend to be more concentrated in Ca and Mg than Na. This might not be the result of groundwater evolution. However, the spring basins are considered as isolated patches created by structures that have to be characterized separately rather than as interconnected. The cations might have originated from the dissolution of the principal minerals that constitute the reservoirs. The carbonates, on the other hand, might have a different origin; they might come from the hydration of the atmospheric carbon dioxide gas and the oxidation of the organic substance that is found naturally in the soil.

The Addis Ababa waters are supplied to the consumers after chlorinating. As the sewerage removal system is far from being complete, polluted waters tend to increase their Cl concentrations as in the case of Ras Mekonnen spring (Arat Kilo area). Waters, which tend to be polluted, have higher Na for their K, HCO3. Therefore, higher Na/K, Na/HCO3, Cl/SO4 and Cl/HCO3 could be considered as an indication of pollution. Polluted waters appear to have higher Cl for their Na, and hence lower Na/Cl. These indicators have more or less happened to be observed in the mentioned spring than the others.

6.4 OTHER CHEMICAL CONSTITUENTS

6.4.1 IRON

Although iron is the second most abundant metallic element in the Earth's outer crust, concentrations present in water generally are small. The chemical behavior of iron and its solubility in water depend strongly on the oxidation intensity in the system in which it occurs; pH is a strong influence as well.

Iron is an essential element in the metabolism of animals and plants. If present in water in excessive amounts, however, it forms red oxyhydroxide precipitates that stain laundry and plumbing fixtures and, therefore, is an objectionable impurity in domestic and industrial water supplies. For this reason, iron determinations are commonly included in chemical analyses of water. A recommended upper limit for iron in public water supplies by World Health Organization (WHO) is 0.3 mg/l.

The plot of the concentrations of Iron from all springs for both seasons (fig. 6-3) showed that concentrations are generally greater for the rainy season than the dry season. This might be due to the relatively high rate of dissolution as a result of infiltrating low pH rain water. Yet, concentrations are not beyond the standard limit (<0.21 mg/l). Iron concentration for Ras Mekonnen spring is as high as those around Entoto mountain indicating its recharge zone might extend northwards in to the rhyolitic rocks. The structural map has also indicated a N-S trending fault line that extends from the mountain to the spring emerging point. As far as the seasonal concentration is concerned, springs closer to Entoto mountain (Akako, Entoto and Gojam-Ber) showed anomalous signatures. On the contrary, springs representing the central and southern parts have shown smaller variation. This is assumed to be the effect of both rainfall distribution and geology. The former being an area receiving the highest rain fall, the effects of dilution and enrichment often occurs on the solutes leached from the acidic rocks. The latter case, however, is an area of relatively receiving less rain fall and a basaltic environment which may not favour as such high rate of leaching. Another possibility is that higher Fe concentrations can be derived from hydrothermally altered rocks. Therefore the rhyolitic rocks of Entoto area, which might have experienced hydrothermal alterations, are expected to provide much iron to the groundwater whenever they are in contact than the basalts.

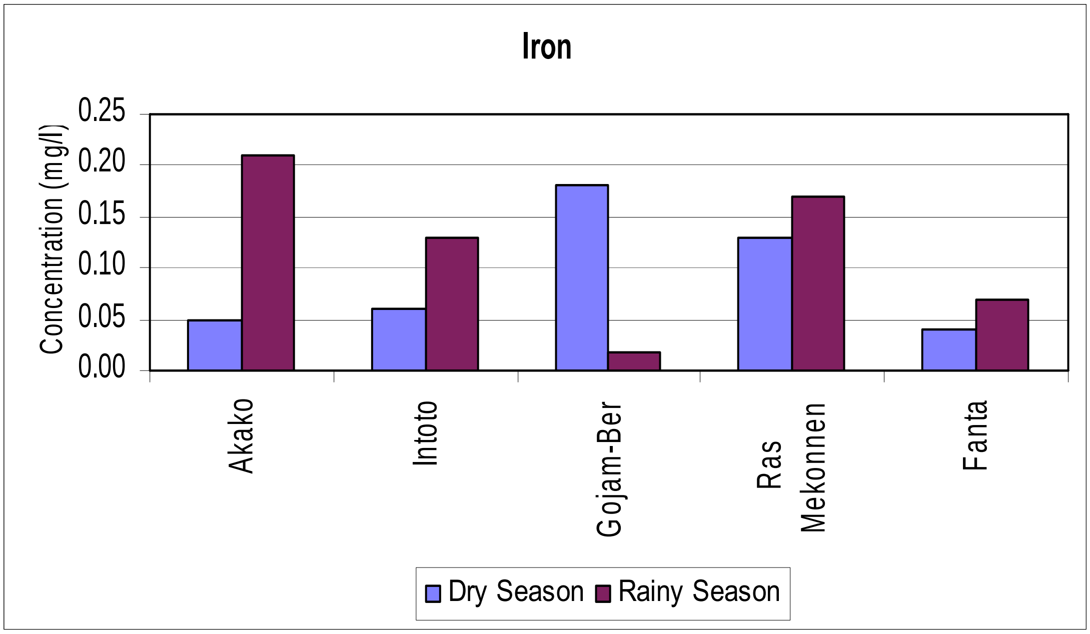


Fig. 6-3: *Spatial and temporal variation of iron concentration in the springs*

Sources of Iron

Igneous rock minerals whose iron content is relatively high include the pyroxenes, the amphiboles, biotite, magnetite, and, especially olivine. The latter is essentially a solid solution whose end members are forsterite (Mg_2SiO_4) and fayalite (Fe_2SiO_4). For the most part, iron in these minerals is in the ferrous, Fe^{2+}, oxidation state, but ferric (Fe^{3+}) may also be present, as in magnetite, Fe_3O_4. When these minerals are attacked by water, the iron that may be released is generally precipitated as can be observed in some small springs along the rhyolitic Entoto mountain range. Springs of the basaltic aquifers have no such indications.

6.4.2 ALKALINITY AND ACIDITY

Most natural waters contain substantial amounts of dissolved carbon dioxide species, which are the principal source of alkalinity. Undissociated dissolved carbon dioxide contributes to acidity rather than to titratable alkalinity and can also be determined by titration using a basic solution.

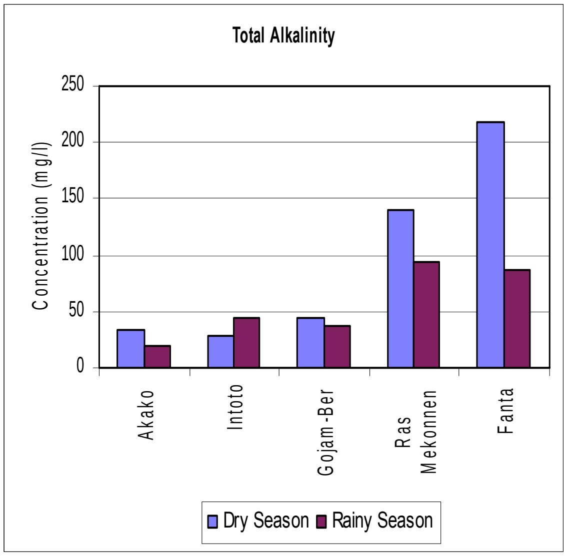
The alkalinity of a solution may be defined as the capacity for solutes it contains to react with and neutralize acid. The property of alkalinity must be determined by titration with a strong acid, and the end point of the titration is the pH at which virtually all solutes contributing to alkalinity have reacted. The end-point pH is the point at which the rate of change of pH per added volume of titrant is at a maximum. The ratio [HCO_3]: [H_2CO_3] will be near 1OO:l at pH 4.4, and the ratio [$HC0_3^{2-}$):[$C0_3^{2-}$] will have a similar value at pH 8.3 at temperatures near 20°C.

The best values for the end points for a particular sample depend on ionic strength and temperature. Analytical procedures may specify a pH value between 5.1 and 4.5, or that of the methyl-orange end point (about pH 4.0-4.6). Sometimes, however, an alkalinity above the phenolphthalein end point (about pH 8.3) is also specified. Thus one may find terms such as “methyl-orange alkalinity,” or its equivalent, “total alkalinity,” and “phenolphthalein alkalinity.” (Hem, 1985). In almost all natural waters the alkalinity is produced by the dissolved carbon dioxide species, bicarbonate and carbonate, and the end points mentioned above were selected with this in mind. Most literatures follow the convention of reporting titrated alkalinity in terms of the equivalent amount of bicarbonate and carbonate. Except for waters having high pH (greater than about 9.50) and some others having unusual chemical composition, especially water associated with petroleum and natural gas or water having much dissolved organic carbon, the alkalinity of natural waters can be assigned entirely to dissolved bicarbonate and carbonate without serious error.

Sources of Alkalinity

The principal source of carbon dioxide species that produce alkalinity in surface or ground water is the CO_2 gas fraction of the atmosphere, or the atmospheric gases present in the soil or in the unsaturated zone lying between the surface of the land and the water table. The CO_2 content of the atmosphere is near 0.03 percent by volume. Soil-zone and unsaturated-zone air can be substantially enriched in carbon dioxide, usually owing to respiration by plants and the oxidation of organic matter. In some natural systems there may be sources of carbon dioxide other than dissolution of atmospheric or soil-zone CO_2. Possible major local sources include biologically mediated sulfate reduction and metamorphism of carbonate rocks. In some areas, outgassing from rocks in the mantle 15 km or more below the surface has been suggested (Irwin and Barnes, 1980).

Ample dissolved CO_2 is available in almost all samples (Fig 6-4) to make the groundwater aggressive. The variation in alkalinity is therefore dependent mainly on the kinds of solute species available that are responsible for the alkalinity and their concentrations. The sources of CO_2 (apart from what is derived from the atmosphere) are also assumed different. Gojam-Ber, Entoto and Akako might derive it from the soil enriched by plant respiration. Those lying towards the central and southern parts of the city (Ras Mekonnen and Fanta) might derive it from oxidation of organic matter.



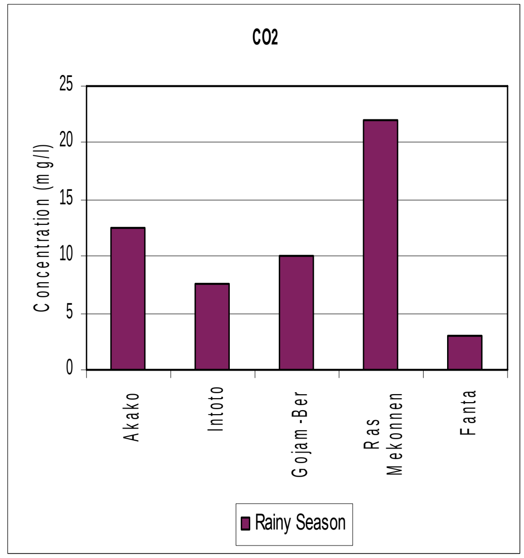


Fig. 6-4: *Spatial and temporal variation of alkalinity and CO_2 concentrations*

6.5 POLLUTION INDICATORS

6.5.1 CHLORIDE

The element chlorine is the most abundant of the halogens. Chloride is present in the various rock types in concentrations lower than any of the other major constituents of natural water. Minerals in which chloride is an essential component are not very common, and chloride is more likely to be present as an impurity. In general, it must be concluded that igneous rocks cannot yield very high concentrations of chloride to normally circulating natural water.

Chloride that is not accounted for by rain is most logically assignable to leaching of sediments. Pollution caused by humans is a major factor in some areas.

Though chloride concentration is very small in all samples, the relative concentration for Ras Mekonnen spring is much higher than the others.

This is an indication of a potential urban pollution effect with which all the others are less affected (fig. 6-5).

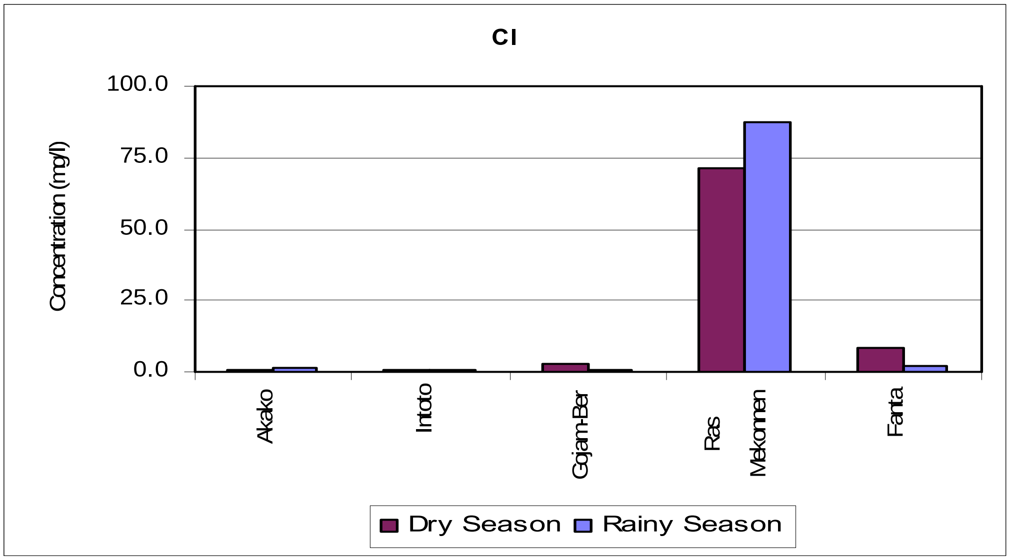


Fig. 6-5: *Spatial and temporal variation of chloride concentration*

6.5.2 NUTRIENTS

Phosphorus is a common element in igneous rock. The fully oxidized (phosphate) form is the only one of significance in most natural water systems. Phosphorus is a component of sewage, as the element is essential in metabolism, and it is always present in animal metabolic waste. High phosphate and nitrate concentration may be related to waste disposal. As pollution indicators, none of the samples have exceeded the permissible limit. However, Ras Mekonnen spring still showed the maximum nitrate concentration showing possible urban pollution (fig. 6-6).

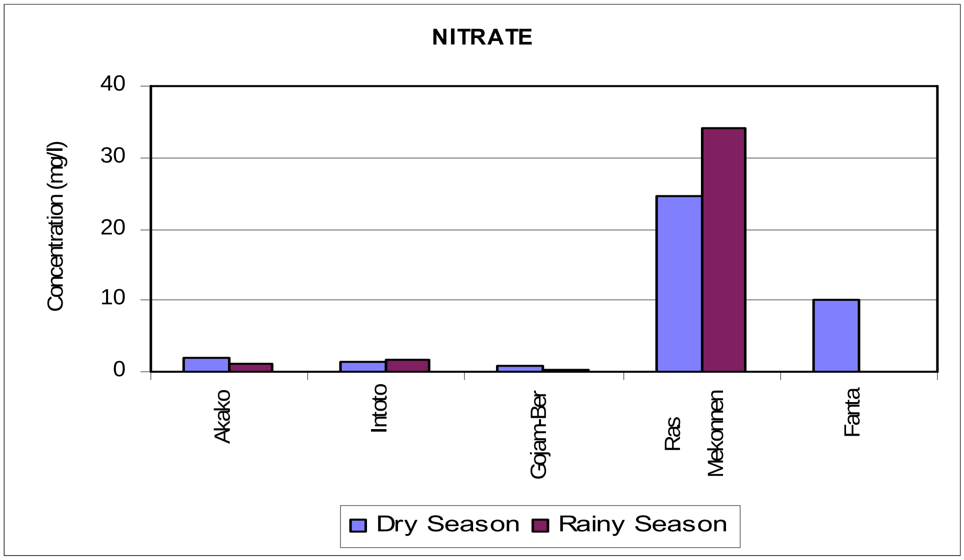


Fig. 6-6: *Spatial and temporal variation of Nitrate concentration*

6.6 SEASONAL CHANGES IN WATER CHEMISTRY

6.6.1 GOJAM-BER SPRING

For the purpose of detecting the seasonal changes in water chemistry, samples have been taken in the months of March and August 2006, each representing the dry and rainy seasons respectively.

However, a general increase with varying magnitude in pH, EC and TDS has been observed between the two seasons (fig. 6-7). These values are relatively smaller for the dry season as compared to the rainy season at Gojam-Ber spring. This shows that the spring is influenced by rain fall so that there is a slight increase in pH and a considerably high increase in TDS and EC. This is all due to the dissolution of feldspars by the infiltrating rain water. The residual clay soil that covers the area is developed as a result of weathering of silicate minerals.

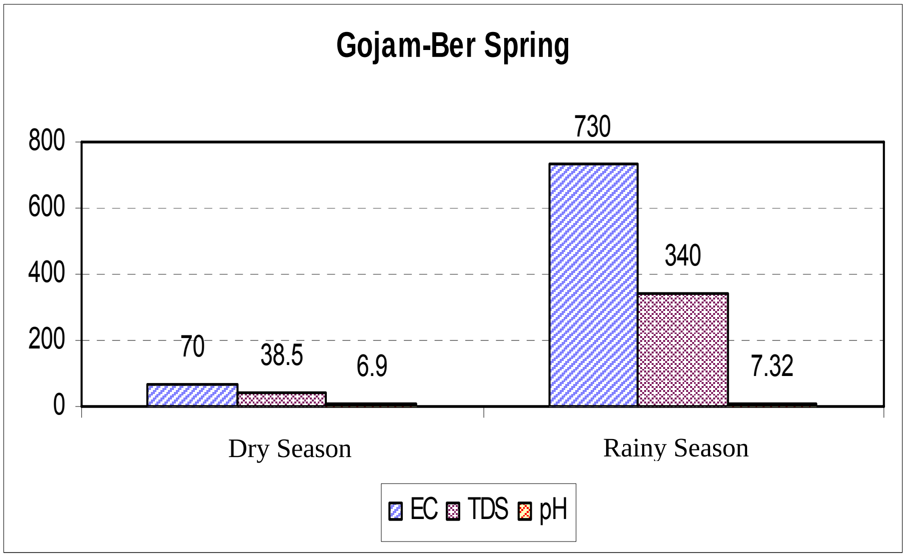


Figure 6-7: *Dry and wet season measurements of EC, TDS & pH of Gojam-Ber spring.*

In general, the composition of the infiltrating water has changed the dry season chemical signature. The graph of the rainfall against spring discharge is also in agreement with this result that there is an increase in the spring discharge before the end of the rainy season (fig 6-8).

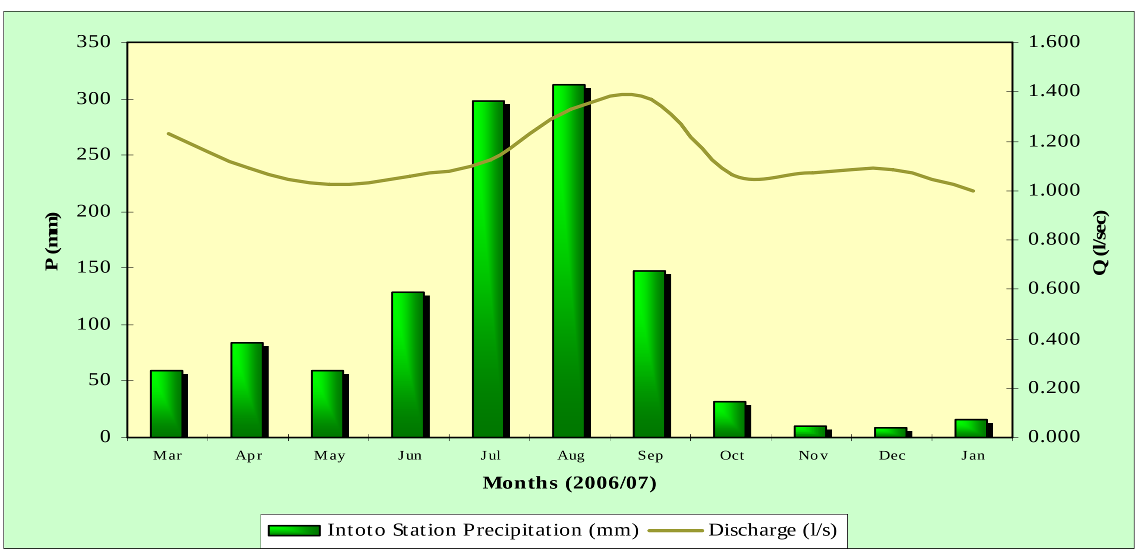


Figure 6-8: *A plot of monthly spring discharge measurement with mean monthly rainfall at Gojam-Ber spring.*

This would also mean that the spring basin is shallow enough for the infiltrating water to reach the spring reservoir in short period of time. The fact that the spring is affected by rainfall can also be justified by the increase in the CO_2 and Nitrate concentrations during the rainy season that might have been injected in to the system by the infiltrated rain water from the atmosphere or shallow depths below the surface.

Out of the five springs considered in this study, isotope analysis results for only four of them (namely Gojam-Ber, Akako, Fanta and Entoto) has been obtained out of which the value obtained for Entoto was found strange enough to be neglected. A zero tritium value for the mentioned spring was not acceptable as it can not be supported by other analytical (such as hydrochemical) techniques and left aside as laboratory analytical error. Therefore, comparison is made only among the two.

According to Berhanu Gizaw (2002), the tritium values in the Addis Ababa waters ranges from 0 to 20 T.U. and so does the data for the mentioned springs. Two of the three samples (Gojam-Ber and Fanta) have < 3 T.U. suggesting that they are relatively old. Akako has the highest tritium value (14.96 TU) and possesses the highest elevation (3150m a.s.l.). Gojam-Ber spring being located at an elevation only 310 m lower than Akako, has got the smallest tritium value (0.39 TU). This can be attributed to the longer distances that might have been traveled by Gojam-Ber before it emerges to the surface as a spring or Gojam-Ber spring is dominated by less conductive geological formations incurring higher residence time. Another possibility is that Gojam-Ber spring could have a wider hydrogeologic basin hence longer flow lines than that of Akako. The reason why Gojam-Ber is highly mineralized can also be related to this explanation (TDS value for Gojam-Ber is higher than that of Akako).

6.6.2 AKAKO SPRING

In a similar manner, water samples representing the rainy and dry seasons have been taken from this spring in the months of August, 2006 and May 2007 respectively. Similar to Gojam-Ber spring, EC and TDS values are very small for the dry season as compared to the rainy season (fig 6-9). A slight increase in pH value has also been observed in the rainy season. This indicates that the spring is influenced by rain fall and the composition of the infiltrating water has changed the dry season chemical signature.

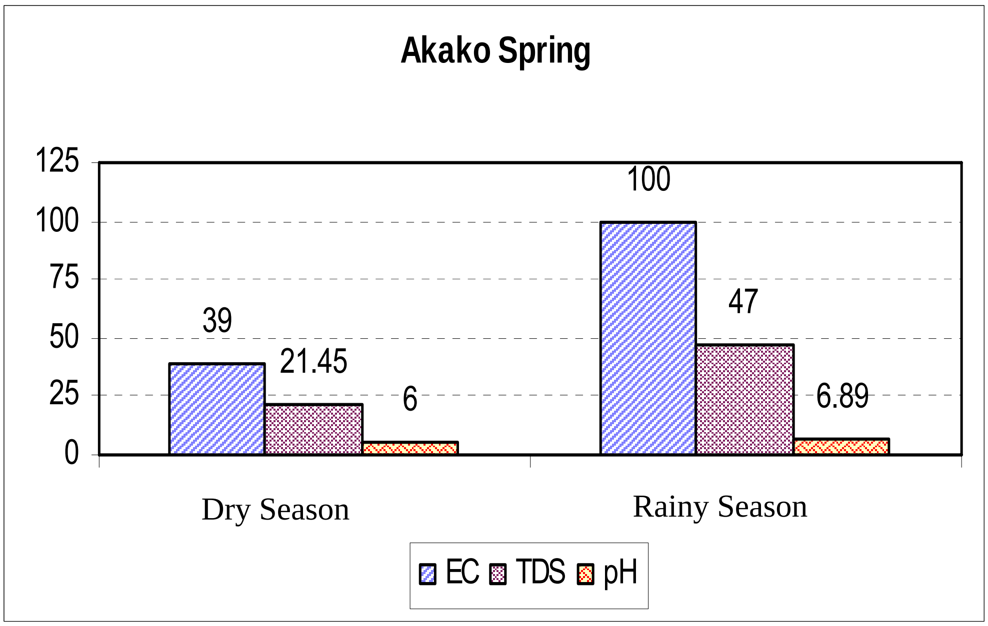


Figure 6-9: *Dry and wet season measurements of EC, TDS & pH of Akako spring.*

An increase in the spring discharge during the rainy season also indicates that infiltrated water has managed to join the groundwater contributing to the spring discharge (fig 6-10).

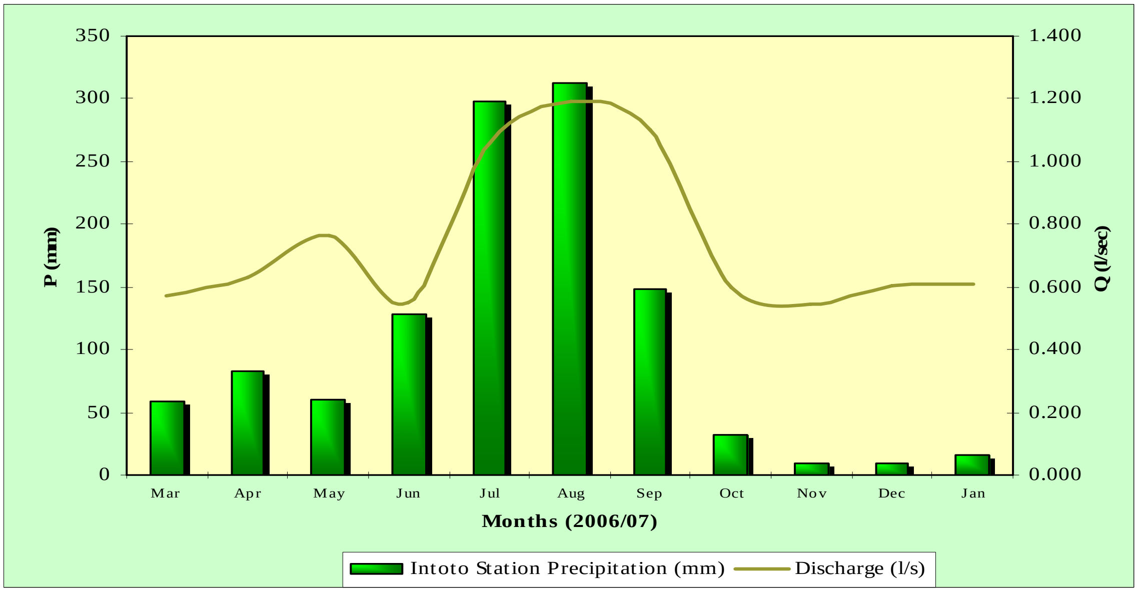


Figure 6-10: *A plot of monthly spring discharge measurement with mean monthly rainfall at Akako spring.*

This would also mean that the spring basin is shallow enough for the infiltrating water to reach the spring reservoir in short period of time. The tritium value for Akako spring is higher than that of Gojam-Ber indicating the shorter distances might have been traveled by Akako spring, hence would have a narrower hydrogeologic basin as compared to that of Gojam-ber. The alternative explanation for this phenomenon is that the transmissivity of the aquifer material at Akako might be better than that of Gojam-Ber.

6.6.3 ENTOTO SPRING

Seasonal water sampling has been conducted in the months of March and August, 2006 for the dry and wet seasons respectively. Regarding the water chemistry, it seems that there is a different situation at this spring site. As can be observed from fig. 6-10, EC and TDS values have rather decreased for the rainy season as compared to the dry season.

However pH has increased is very slightly (fig 6-11). It is therefore possible to infer that the effect of the infiltrating water to change the chemical signature of the groundwater may not be observed during a single hydrologic year. Rather the observed dry season signature might correspond to the wet season of the previous year and the observed wet season signature might serve as an input for the next dry season.

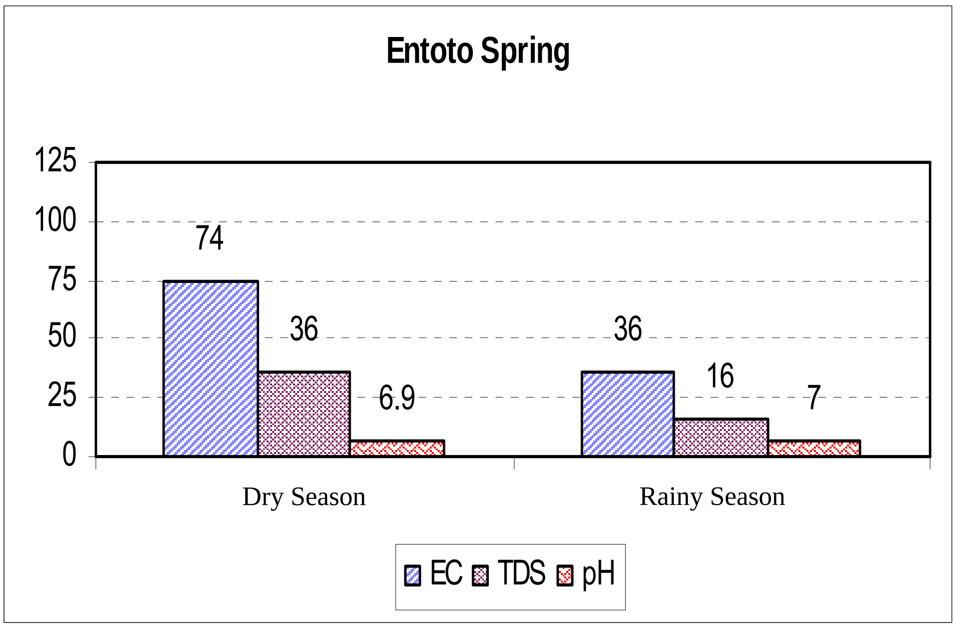


Figure 6-11: *Dry and wet season measurements of EC, TDS & pH of Entoto spring.*

The fact that the effect of the rainfall is observed on the spring discharge later in the month of September to November (fig, 6-12) can be related to the explanation given above. This means that due to the relatively higher residence time of the infiltrated water the change in the chemical signature of the water would persist during the dry season. However during the peak rainy season, the infiltrated water has not yet affected the discharge so that the TDS and EC values might indicate the late dry season signature of the previous season.

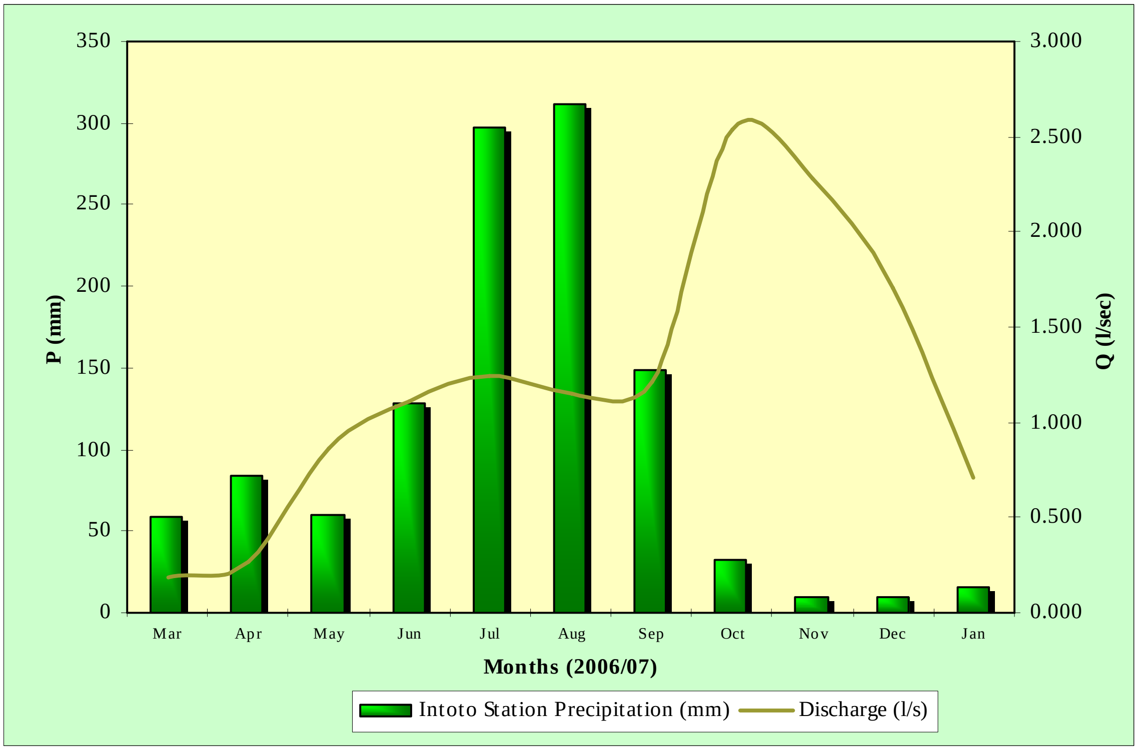


Figure 6-12: *A plot of monthly spring discharge measurement with mean monthly rainfall at Entoto spring.*

6.6.4 FANTA SPRING

Seasonal water sampling has been taken place in the months of March and August, 2006 for the dry and wet seasons respectively. The analysis result showed that EC, TDS and pH values have increased for the rainy season as compared to the dry season (fig. 6-13). It is therefore inferred that dissolution of feldspars by infiltrating water was a phenomenon taking place somewhere within the spring recharge area that is assumed to extend very far to the NE direction. Had it not been for the dissolved minerals in the infiltrating water, the indicated parameters wouldn't have shown changes. Another possibility is that antropogenically induced constituents can also be responsible for the observed changes in the mentioned parameters.

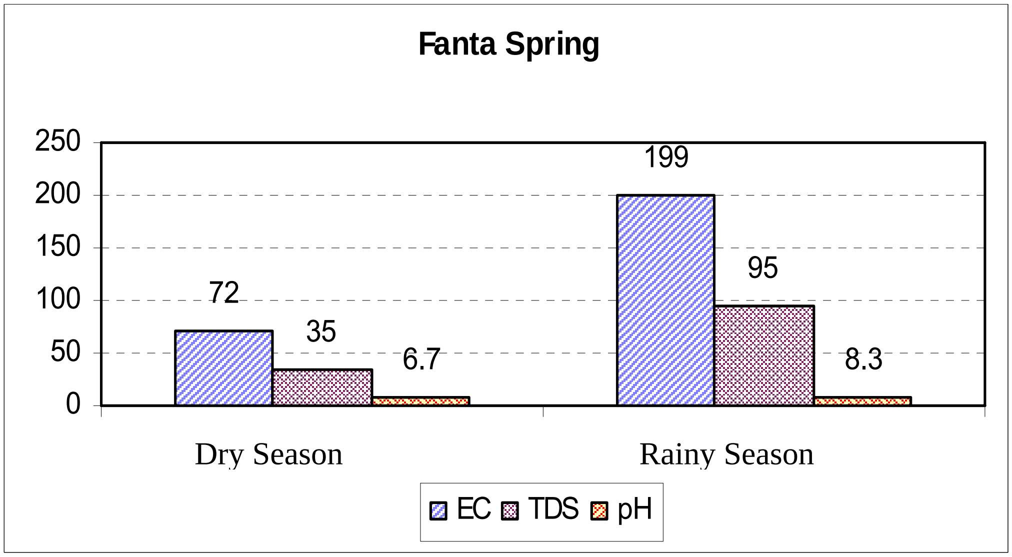


Figure 6-13: *Dry and wet season measurements of EC, TDS & pH of Fanta spring.*

Similar to Intoto spring the effect of the rainfall is observed on the spring discharge later in the month of September to November (fig. 6-14). Since the transmissivity in the Fanta spring area is higher, the possible cause for the late effect of the infiltrated water is the long distance it might have traveled.

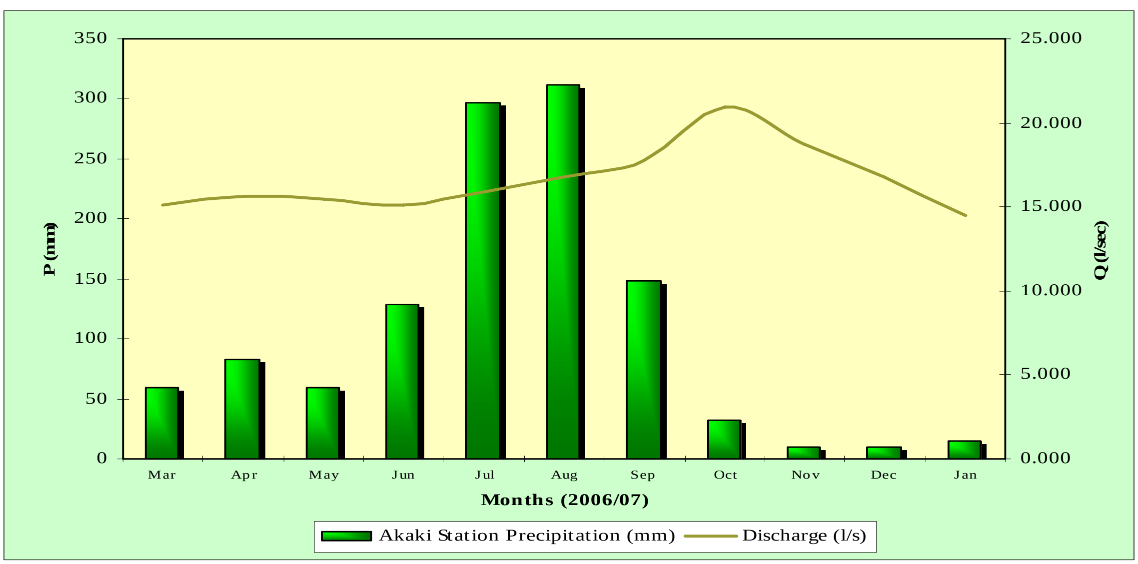


Figure 6-14: *A plot of monthly spring discharge measurement with mean monthly rainfall at Fanta spring.*

6.6.5 RAS MEKONNEN SPRING

Seasonal water sampling for this spring was conducted in the months of August, 2006 and May 2007 for the dry and wet seasons respectively. There is a relative increase of EC and TDS values for the rainy season as compared to the dry season. As the seasonal change is not that big, it might show that the leaching of feldspars in the basaltic media is not that significant as in the old acidic rocks of Entoto mountain (fig. 6-15).

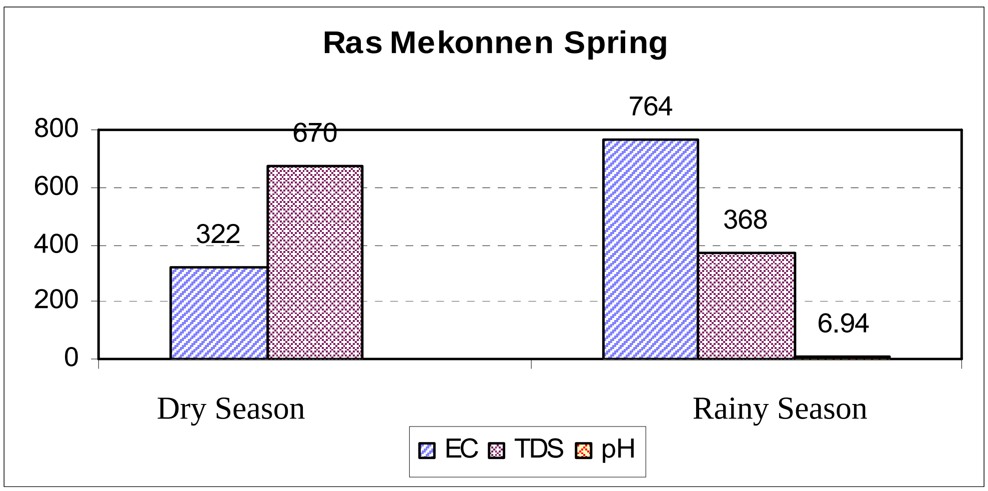


Figure 6-15: *Dry and wet season measurements of EC, TDS & pH of Ras Mekonnen spring.*

In this spring, the effects of both the irregular small rainy season that appears in March and April and the main rainy season that appears between June and September have been observed. A smaller discharge peak was observed in July as a result of the former and in November due to the latter (fig. 6-16).

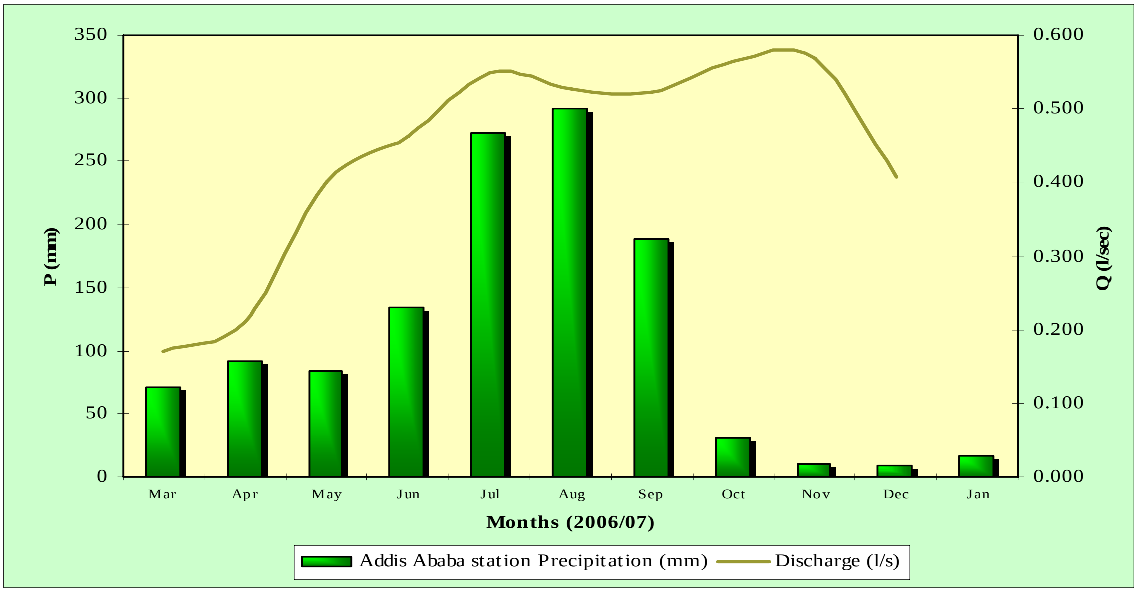


Figure 6-16: *A plot of monthly spring discharge measurement with mean monthly rainfall at Ras Mekonnen spring.*

CHAPTER SEVEN

ANALYSIS MODELS OF THE EMPTYING CURVES

7.1 GENERAL

The governing factors that control a spring flow, the discharge at a given time, the storage properties and the duration of emptying of a spring source are among the variables that can be determined through modeling of the emptying (recession) curves of a spring. Recession curves contain information on storage properties in different types of media such as porous, fractured, cracked lithologies and karst. Recession curve analysis provides a function that quantitatively describes the temporal discharge decay and expresses the drained volume between specific time limits (Hall, 1968).

Amit et al. (2002) suggests that the interpretation of spring recession curves may be valid for many lithologies other than karst, including terrains composed of fractured rock and for low flow springs. The authors' analysis included springs with discharges of 0.6 to 140 l/m, implying the method is valid even at extremely low discharge rates. The period of discharge monitoring required to adequately characterize a spring (and the associated flow paths) can depend on rainfall. In such cases, widely separated rainfall events with easily correlated peaks give the best results. Closely spaced rainfall events that result in complex overlapping peaks, where the spring discharge does not return to base flow after each rainfall event, provide little help in evaluating flow conditions.

In this particular study, the selected springs exist in and close to Addis Ababa. As Addis Ababa is located at the western shoulder of the Main

Ethiopian Rift (MER), the area is characterized by a system of faults, joints and fractures that control the flow of groundwater and emergence of springs. The geohydrologic settings on which the springs are resting is also different. Periodic manual discharge measurements with a stopwatch and a container of known volume were made.

The main parameters of the spring sources have been estimated by means of the formula given by Mangin (1970). Zurawska (2001) used this formula for hydrogeological study of springs on geologically and tectonically complex area in Poland. The same formula has been used by Civita and Vigna (1985) and Sanna (1995) for the modeling of karstic sources. As Tamiru Alemayehu (1998) used it for low yield springs since the type of emptying of sources in volcanic areas is similar to that of karstic sources, the formula of Mangin (1) has also been applied here.

$$Q_t = Q_{ro} e^{-\alpha t} + q_o \frac{(1 - \eta t)}{(1 + \varepsilon t)} \qquad (1)$$

Where:

Q_t = Discharge at time t.

Q_{ro} = Discharge at the beginning of exhaustion.

η = Coefficient of infiltration rate.

ε = Coefficient of flow heterogeneity.

q_o = Initial contribution of infiltration.

The analyzable curve of emptying with the model of Mangin is composed of two parts: the first term of equation (1) represents the exponential function of Maillet in regimen not influenced by infiltration (in the absence of the effect of rainfall). The other term of equation (1), represents the function of Mangin that describes the process of emptying in the presence infiltration until the time $t_i = 1/\eta$. Integrating equation

(1), the first term gives annual regular reserve (2). This refers to the volume of water that remains regularly in the aquifer.

$$W_r = \int_0^{\infty} Q_{ro} e^{-\alpha t} dt \qquad (2)$$

On the other hand, the integration of the second term gives the infiltration volume (3) starting from the maximum peak of the year which had the precipitation contributions.

$$V_i = \int_0^{t_i} q_o \frac{(1 - \eta t)}{(1 + \varepsilon t)} dt \qquad (3)$$

According to Mangin (1970), the coefficient η represents the infiltration rate that is inversely proportional to the duration of infiltration. The coefficient ε, on the other hand, controls the concavity of the curve. Hence, a high value of ε represents fast infiltration in the beginning that gradually becomes slower.

7.2 MODELLING OF THE EMPTYING CURVES

In the beginning attempt was made to carry out the modeling work on six springs. In the end Yeka spring was excluded due to insufficient data for analysis. Consequently, modeling of the emptying curve has been executed on five spring sources. The analyzed curves have been plotted starting from the maximum peak flow of a year, including the periods of exhaustion. For Entoto and Fanta springs the maximum peak corresponds to 27th September. For Gojam-Ber, Akako, Ras Mekonnen and Yeka springs the maximum peak corresponds to September 30, August 28, July 25 and November 29 respectively. The effect of infiltration on the discharge of the sources cancels after a certain period of time (40 days for Gojam-Ber, 62 days for Akako, 82 days for Intoto, 96 days for Fanta and 63 days for Ras Mekonnen).

7.2.1 GOJAM-BER SPRING

LOCATION AND ACCESSIBILITY

This spring is found in the northern part of Addis Ababa along the Intoto mountain range geographically located at UTM coordinates of 470750mE and 1003800mN at an elevation of about 2840m above mean sea level. It is a spring developed and owned by the Addis Ababa Water and Sewerage Authority (AAWSA) for water supply of the community residing at closer proximity to the spring. The average monitored discharge of the spring is about 1.13 l/s. A reservoir of 50 cubic meter capacity has been built some 850m south east of the spring (fig. 7-1).

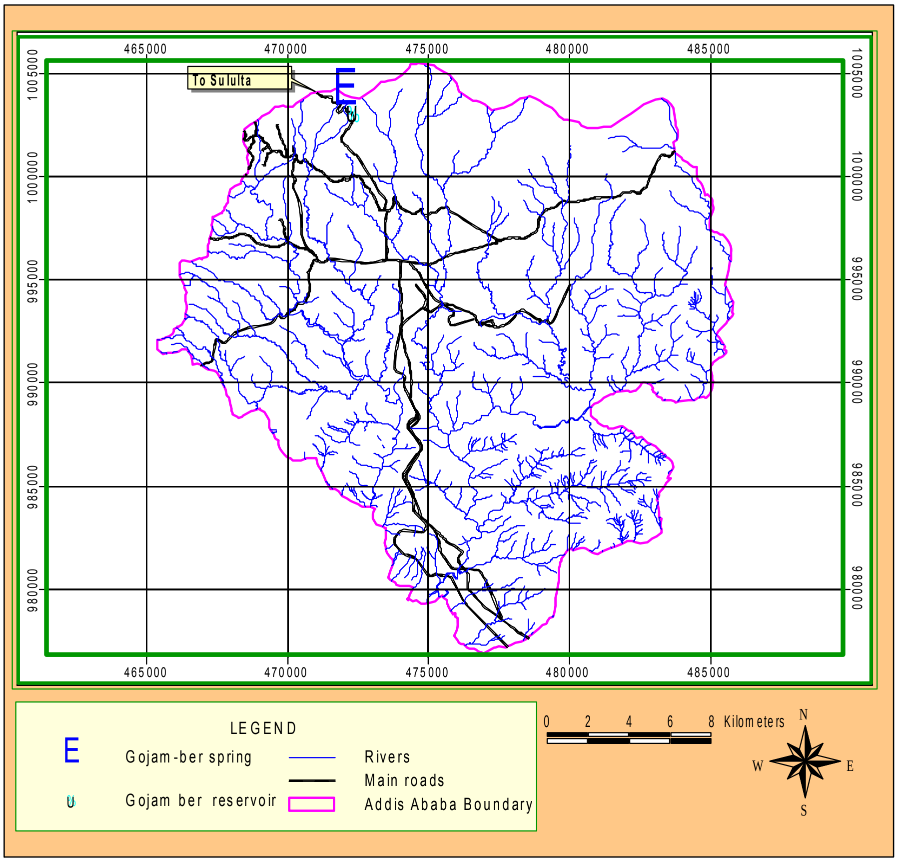


Figure 7-1: *Location map of Gojam-Ber spring*

The spring spot, which can be accessed through the main Addis Ababa-Gojam high way, is located off the road towards Intoto mountain while the reservoir is very close to the road. Depending on the path followed one has to walk 350 to 850 meters off the main road to reach at the spring spot.

LOCAL GEOLOGICAL AND HYDROGEOLOGICAL SETTING

Large part of the northern portion of Addis Ababa is composed of acidic geological formations that belong to the Entoto silicics. These rocks are composed dominantly of rhyolites and trachytes, with rhyolites covering much of the western portion of the Entoto ridge with their maximum thickness. Gojam-Ber spring, being located towards the western portion of the ridge emerges from the rhyolites. These rocks are the oldest in the area to be subjected to prolonged periods of weathering. As determined by Morton et.al, 1979 they date back to 22 MY. Hence it is common to see them deeply weathered along the slopes of the ridge.

The complex tectonic setting of the area is explained by faulting, flow banding, folding and jointing of the rocks. Faults, fractures and joint systems can therefore be the main paths along which groundwater flow occurs. The orientations of these fractures are so complex that the fracture that takes the infiltrated water to the spring eye can hardly be traced. However, Satellite image analysis revealed that a major E-W trending fault line and a NE-SW trending fault intersect very close to the spring spot. These faults must have exposed the fractures along fault planes for groundwater to flow out or they served as a channel along which the spring water emerged.

As far as the hydrogeological setting of the area is concerned, the spring is located at or very close to the water divide (recharge area) where the Blue Nile and the Awash river basins are separated. Due to the old age of the rocks and subsequent high degree of weathering, there is a high chance for fractures to be filled with weathering products. This will tend to minimize the transmissive nature of the rocks affecting the spring yield negatively. Northwards from the spring spot exists the Sululta plain from where the spring might be recharged. This plain is covered by rhyolites and basalts of ages older than the Entoto silisics. The effect of insitu weathering in the plain will result in the development of thick soil profiles leading to retarded infiltration of precipitation that can still be a factor to affect the spring discharge negatively.

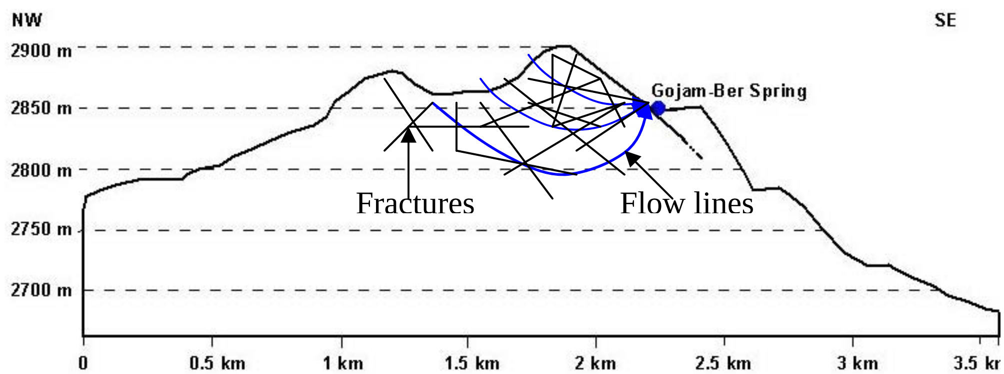


Figure 7-2: *Mode of emergence of Gojam-Ber spring*

Figure 7-3: *Spring capping structure (left), Weathered and fractured rhyolite (right)*

FLOW MODEL OF GOJAM-BER SPRING

The curve has been initially corrected so as to eliminate the irregularity (fig. 7-4 below).

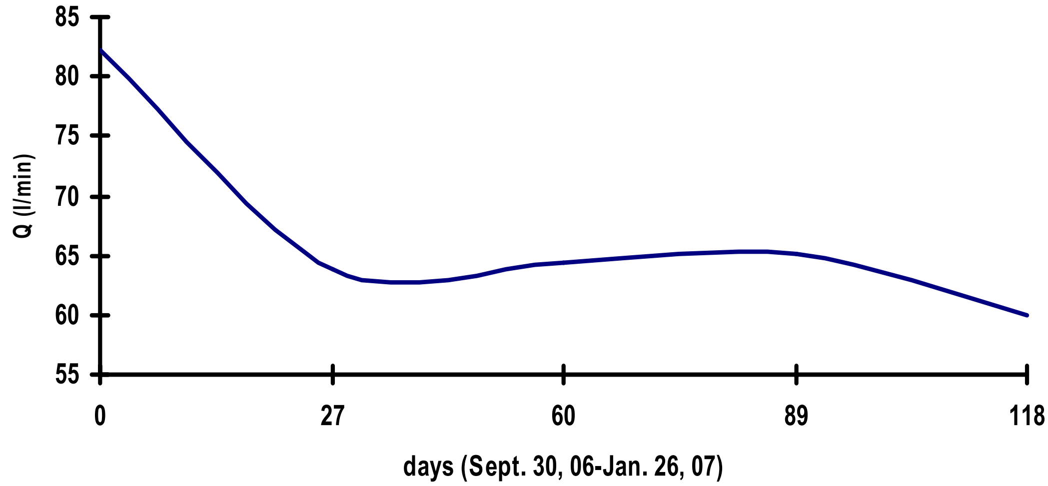


Figure 7-4: *Recession curve of Gojam-Ber Spring*

The same curve when plotted on a semi-logarithmic diagram (fig. 7-5), it is possible to determine Q_{ro} as an intersection of the best fit line with the Y-axis (discharge). This point, therefore, shows the spring discharge at that time if there wasn't any input from infiltrated precipitation.

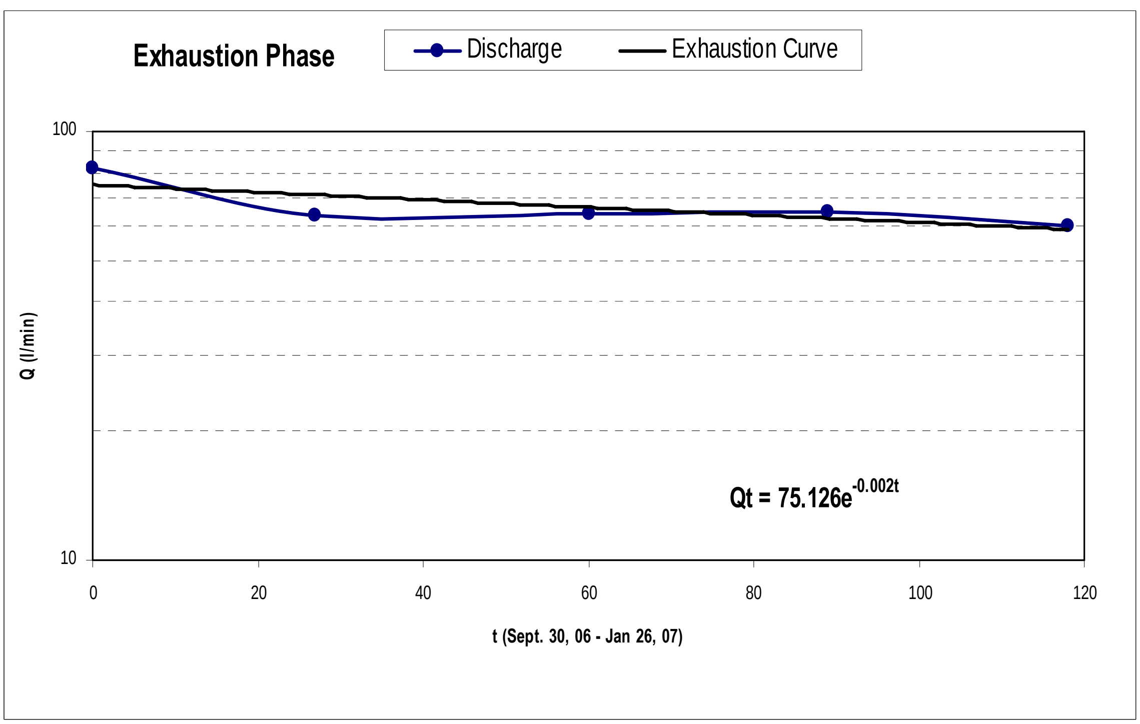


Figure 7-5: *Semi-log plot of the recession curve of Gojam-Ber Spring*

The exponential equation of the exhaustion curve, from which Q_{ro} is determined, takes the form of the equation (4) below:

$$Q_t = Q_{ro} e^{-\alpha t} \quad (4)$$

Once Q_{ro} is determined, it is possible to solve for α in to equation (4) as Q_t and t are the discharge at the end of exhaustion and the total duration of exhaustion respectively-hence are known.

Resolving equation (4) for α:

$$\alpha = \frac{(LNQ_{ro} - LNQ_t)}{t} \quad (5)$$

From equation (5) the following α value can be obtained by substituting the values:

$$\alpha = \frac{(LN75.12 - LN59.34)}{118} = 0.001998$$

The corresponding expression of Maillet after inserting the calculated α values is:

$$Q_t = Q_{ro} e^{-0.001998 \quad t}$$

In order to calculate q_t it is necessary to subtract, for every value of t (starting from t = 0), the value of Q on the curve from that of the straight line of the Best Fit. In doing so, a new curve (labeled as q_o in the graph below) is obtained. The curve is called curve of decrement which is represented by equation (6):

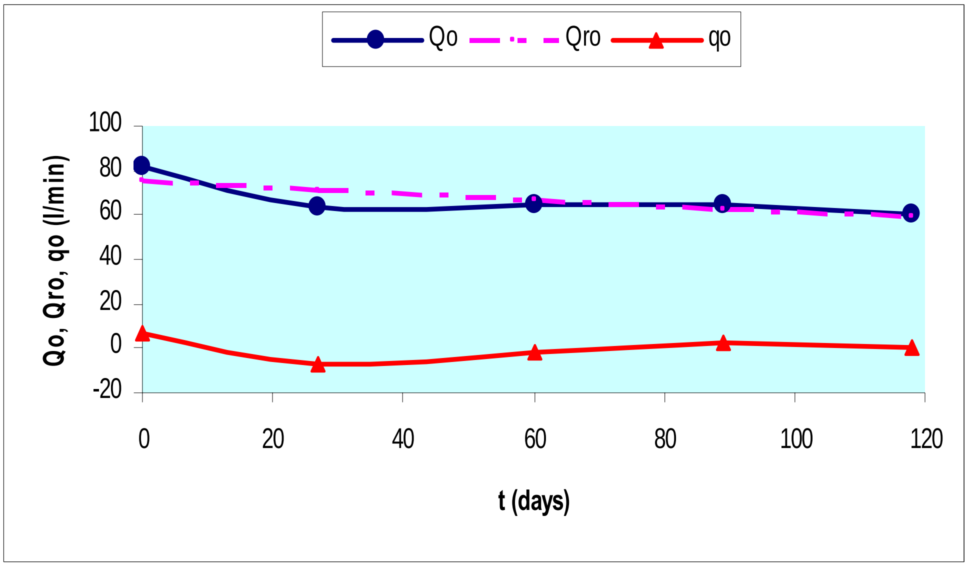


Figure 7-6: *Decrement curve of Gojam-Ber Spring*

$$q_t = q_o \frac{(1 - \eta\, t)}{(1 + \varepsilon\, t)} \qquad (6)$$

Using the equation of Mangin the value of η can be obtained from $1/t_i$. The value of the parameter ε can be calculated by integrating both sides of equation (6), from t = 0 to t = t_i, giving equation (7):

$$V_i = q_o[\tfrac{1}{\varepsilon}(1 + \tfrac{\eta}{\varepsilon})LN\,(1 + \varepsilon t_i) - \tfrac{\eta t_i}{\varepsilon}] \qquad (7)$$

from which ε can be obtained by iterative method once V_i is known:

$$43921\ .28 = 7.08[\tfrac{1}{\varepsilon}(1 + \tfrac{0.025}{\varepsilon})LN\,(1 + \varepsilon \times 40) - \tfrac{0.025 \times 40}{\varepsilon}]$$

ε = 0.52

Therefore, the curve of decrement represented by the function of Mangin for Gojam-Ber spring looks like the following:

$$q_t = 7.08\frac{(1 - 0.03704t)}{(1 + 0.52t)}$$

WATER STORAGE

Dynamic storage (W_o), refers to the reserve of the sources to the maximum piezometric height of the reservoirs during the period of exhaustion ($t=t_o$), (Celico, 1988). Introducing Q_{ro} and α, W_o can be calculated using the simplified formula of Maillet (8).

$$W_0 = \frac{Q_{ro}\,1440}{\alpha} \qquad (8)$$

where: Q_{ro} in l/min

Substituting the appropriate values for the spring gives:

$$W_0 = \frac{75.12 \times 1440}{0.001998}$$

$$W_0 = 54131536 \text{ litres}$$

The regular reserve (W_r), which refers to the volume of water stored between the minimal piezometric level (as piezometric level can fluctuate) and the measured level at the end of the time of the exhaustion (Celico, 1988). W_r is determined with the following formula (9).

$$W_r = \frac{Q_{ro}\,1440}{\alpha e^{\alpha t}} \qquad (9)$$

where: Q_{ro} in l/min

Accordingly, W_r for the spring will be:

$$W_r = \frac{75.12 \times 1440}{0.001998 \times e^{0.001998 \times 118}}$$

$$W_r = 42760387 \quad \text{litres}$$

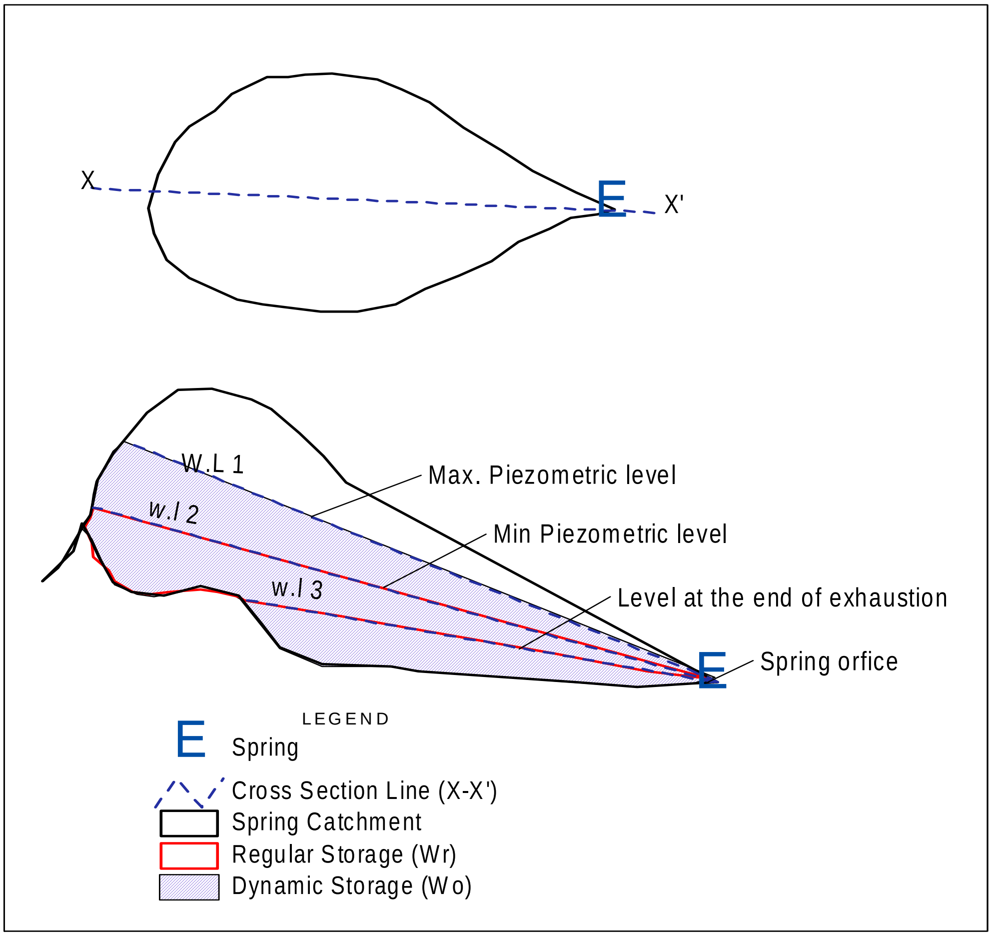


Fig. 7-7: *Schematic presentation of the dynamic and regular reserves.*

The difference between the dynamic storage and the regular reserve gives the ability to emptying (10). This refers to the volume of water freed during the time of exhaustion.

$$\Delta W = W_0 - W_r \qquad (10)$$

$$\Delta W = 54131536 - 42760387$$

$$\Delta W = 11371149 \text{ litres}$$

The values of the emptying ability correspond to the dynamic resources at time t = 0. The values of the rate of renewal (T_r) per cent represents the quantity of water that has infiltrated from the total amount that was available to renew the aquifer storage in the course of the hydrologic year, equation (11). The minimum time of renewal (t_m) expresses the minimum time necessary to replenish the water volumes of dynamic storage, equation (12).

$$T_r = (\Delta W/W_0)100 \qquad (11)$$

$$T_r = (11371149/54131536)100$$

$$T_r = 21.01\ \%$$

$$t_m = W_0/\Delta W \text{ (in years)} \qquad (12)$$

$$t_m = 54131536/11371149$$

$$t_m = 4.76 \text{ years}$$

Summary of the model-calculated values of the different variables previously discussed are presented in Table 7-1 below.

Spring	Q_o (l/min)	Q_{ro} (l/min)	q_o (l/min)	α	W_0 (l)	W_r (l)	ΔW (l)	T_r (%)	t_m (years)	t_i (d)	t (d)	η	ε	V_i (l)	DT_t
Gojam-Ber	82.2	75.12	7.08	0.001998	54131536	42760387	11371149	21.01	4.76	40	118	0.02500	0.52	43921.28	500.42

Table 7-1: Summary of model calculated parameters for Gojam-Ber spring

MODEL LAYOUT AND CALCULATED RESULTS

Below is shown the EXCELL-based model and the corresponding calculated parameters for Gojam-Ber Spring.

Gojam Ber Spring (SP-03)		
	UTM-EASTING	**UTM-NORTHING**
	470750	*1003800*
PROVIENCE	**LOCALITY**	**USE**
Addis Ababa	*Gojam Ber*	*Water Supply*
DEVELOPMENT	**EMERGENCE**	**REGIME**
Captured	*Localized*	*Perennial*
	MEASURABLE	
	yes	
Hydrogeologic Study:	Model of Maillet	Analysis of the hydrograph
Minimum Discharge Q_{min}=	0.999	l/sec
Maximum Discharge Q_{max}=	1.370	l/sec
Average Monitored Discharge Q_{avg}=	1.131	l/sec
Percent of variability Rv=	32.790	%
Year (Phase) 2006		
Coefficient of exhaustion α =	0.001998332	
Duration of phase exhaustion t =	118	d
Qo Calculated Qo=	1.252	l/sec
Q_t Calculated Q t =	0.989	l/sec
Dynamic Storage W_o=	54131.536	m^3
Regular Storage W_r=	42760.387	m^3
Capacity of emptying ΔW=	11371.149	m^3
Sustainable flow duration DT_t=	500.42	d
Recharge (renewal) rate T_{rin}=	21.01	%
Recharge Duration (time of renewal) t_{rin}=	4.76	Years

Table 7-2: Model lay out and calculated results of Gojam-Ber spring

7.2.2 AKAKO SPRINGS

LOCATION AND ACCESSIBILITY

A couple of closely spaced springs are together known by this name. The springs are found behind the Intoto mountain range towards the Abbay river basin. Though it lies out of the boundary of Addis Ababa, it is only about 2.5 km from the nearest city boundary and about 7 kms northeast of Gojam-Ber spring. Their geographical location is represented by UTM coordinates of 477450mE, 1006250mN and 478600mE, 1006350mN with elevations of about 3140m and 3150m above mean sea level respectively. The springs are developed and used by the Addis Ababa Water and Sewerage Authority (AAWSA) for water supply of the community southeast of the spring. The springs have been capped from their respective discharging points and are brought in to a single system to be conveyed to Addis Ababa. The collective average discharge of the springs after monitoring for one hydrologic cycle was found to be 0.75 l/s. A reservoir of 50 cubic meter capacity has been built some 4.3 Km southwest of the spring at a place known as Ras Seyoum village. Following the Sidist Kilo-Shiromeda road and passing right by Intoto Mariam Church, one has to go further to the northeast along an all weather gravel road to reach the spring spots. The location map of the spring site is shown in fig. 7-8 below.

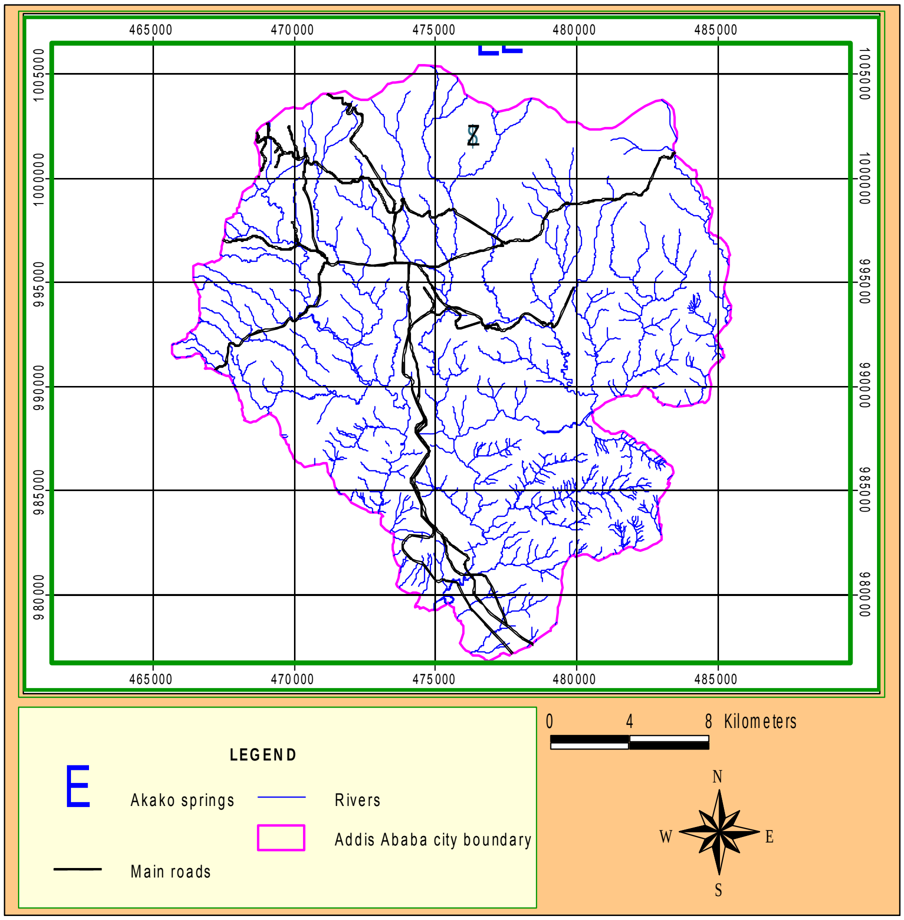


Figure 7-8: *Location map of Akako spring*

LOCAL GEOLOGICAL AND HYDROGEOLOGICAL SETTING

The Intoto silicics, that cover the Intoto mountain range, also extends further to the north for at least 3 kms on the other side of the ridge where the Akako springs are located. Being in the same vicinity with Gojam-Ber spring, the spring is located on similar geological settings. Hence rhyolites are the main rock units existing in the area. However, the topography at Akako area is gentler and the thickness of the rhyolites would be smaller. From structural point of view, Akako spring is crossed by NE-SW trending fault line which in turn is crossed by an E-W trending major fault passing north of Gojam-Ber spring. The groundwater therefore gets way to emerge along the slope through the fractures (fig. 7-9).

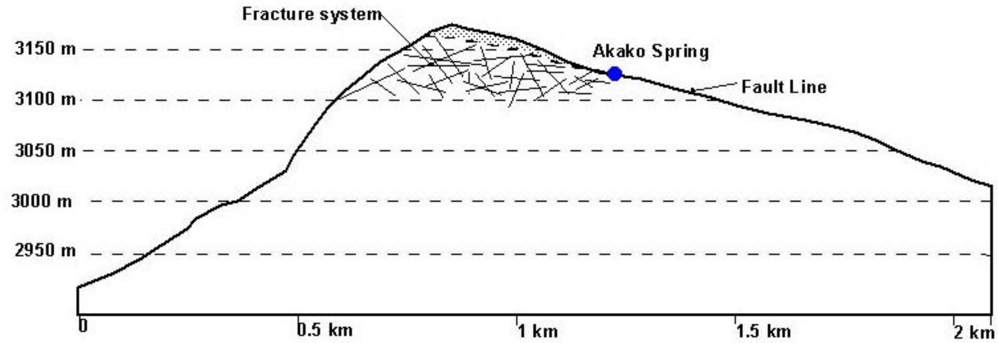


Figure 7-9: *Mode of emergence of Akako spring*

Fig. 7-10: *Akako Spring capping structure (left) fractures in rhyolites around the spring.*

The hydraulic characteristics of the rocks is also similar to that of Gojam-Ber area spring except for the local variations as a result of the different degrees of weathering, density and/or aperture of fractures and other similar factors. Their variation in their average discharge can also be explained from the view point of the mentioned factors.

FLOW MODEL OF AKAKO SPRING

The smoothed exhaustion curve of this spring is as shown below (fig. 7-11).

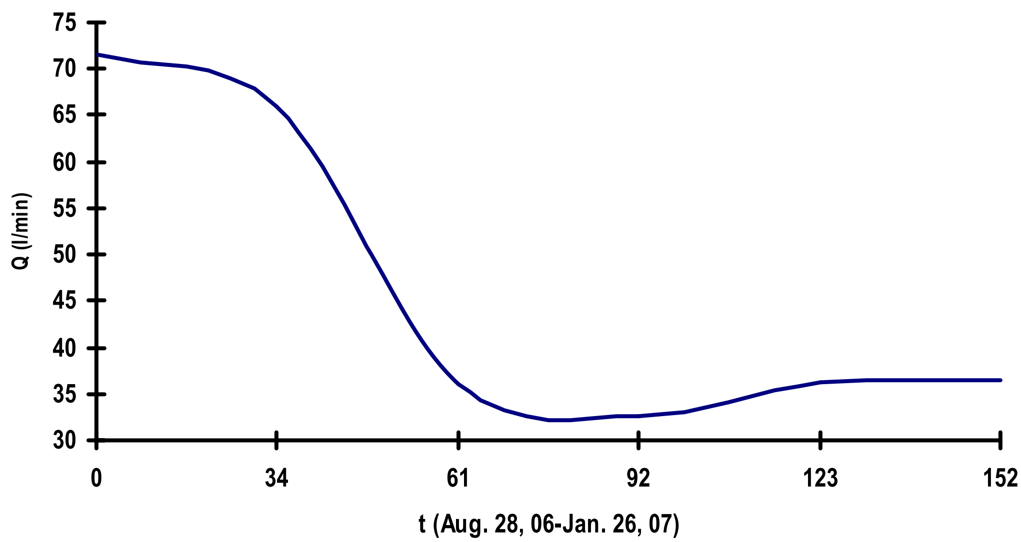


Figure 7-11: *Recession curve of Akako Spring*

Intersection of the best fit line with the Y-axis from a semi-logarithmic diagram of the above curve gives Q_{ro}.

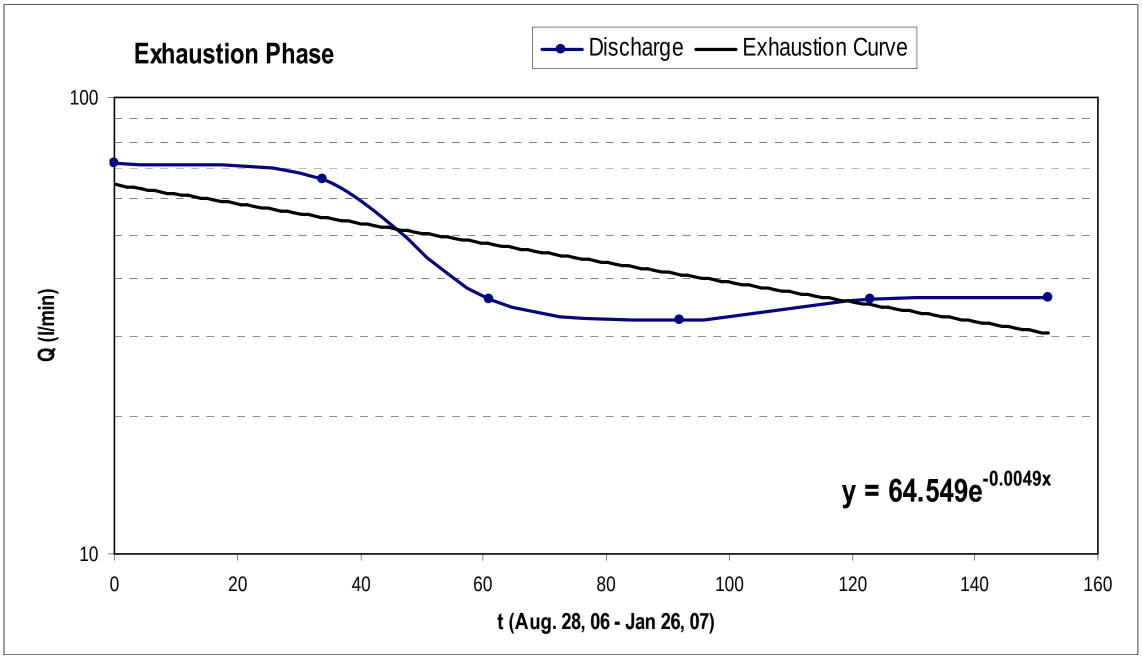


Figure 7-12: *Semi-log plot of recession curve of Akako Spring*

The exponential equation of the exhaustion curve, from which Q_{ro} is determined will be:

$$Q_t = Q_{ro} e^{-\alpha t}$$

Hence, α will be:

$$\alpha = \frac{(LN64.56 - LN30.66)}{152} = 0.004899$$

The corresponding expression of Maillet after inserting the calculated α values is:

$$Q_t = Q_{ro} e^{-0.004899 \quad t}$$

The curve of decrement and the corresponding equation is:

$$q_t = 7.02 \frac{(1 - 0.01613\ t)}{(1 + 0.22\,t)}$$

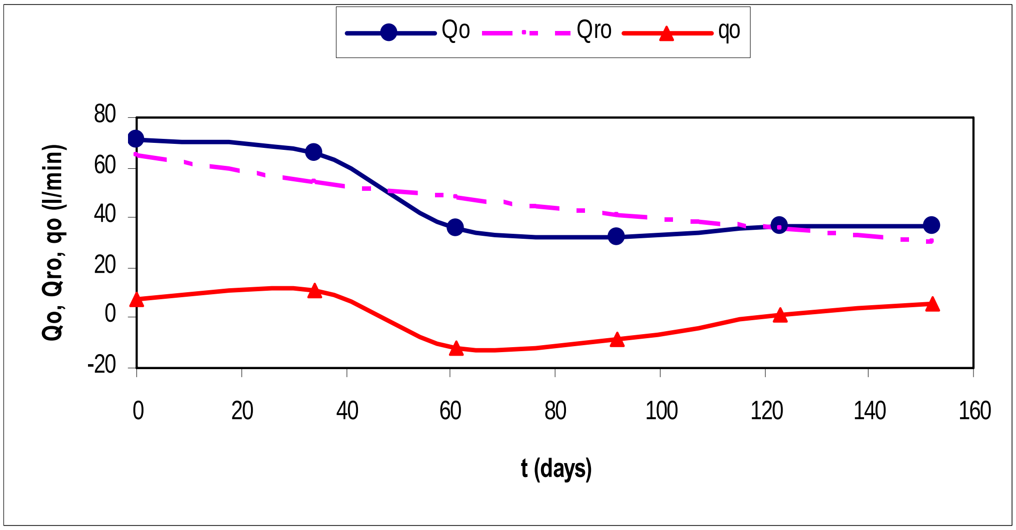


Figure 7-13: *Decrement curve of Akako Spring*

Using the equation of Mangin the value of η can be obtained from $1/t_i$.

Hence,

$$\eta = \frac{1}{62}$$

$$= 0.01613$$

In the same manner as for the previous case, given that the value of V_i is known, the value of the parameter ε can be calculated using the following formula by iterative method:

$$V_i = q_o[\tfrac{1}{\varepsilon}(1 + \tfrac{\eta}{\varepsilon})LN\,(1 + \varepsilon t_i) - \tfrac{\eta t_i}{\varepsilon}]$$

$$86782 = 7.02[\tfrac{1}{\varepsilon}(1 + \tfrac{0.01613}{\varepsilon})LN\,(1 + \varepsilon \times 62) - \tfrac{0.01613 \times 62}{\varepsilon}]$$

$\varepsilon = 0.22$

The calculated values are presented in Table 7-3 below.

Spring	Q_o (l/min)	Q_{ro} (l/min)	q_o (l/min)	α	W_0 (l)	W_r (l)	ΔW (l)	T_r (%)	t_m (years)	t_i (d)	t (d)	η	ε	V_i (l)	DT_t
Akako	71.58	64.56	7.02	0.004899	18976909.6	9012223.6	9964686	52.51	1.90	62	152	0.01613	0.22	86782	204.13

Table 7-3: Summary of model calculated parameters for Akako spring

Therefore the curve of decrement represented by the function of Mangin, for the analyzed sources will look like the following:

$$q_t = q_o \frac{(1-\eta t)}{(1+\varepsilon t)}$$

$$q_t = 7.02 \frac{(1-0.01613t)}{(1+0.22t)}$$

WATER STORAGE

The Dynamic Storage (W_o) of the spring will be:

$$W_0 = \frac{Q_{ro}\,1440}{\alpha} \qquad \text{where: } Q_{ro} \text{ is in l/min}$$

$$W_0 = \frac{64.56 \times 1440}{0.004899} \text{ litres}$$

$$W_0 = 189769096 \text{ litres}$$

The regular reserve (W_r) is determined with the following formula.

$$W_r = \frac{Q_{ro}1440}{\alpha e^{\alpha t}}$$ where: Q_{ro} in l/min

$$W_r = \frac{64.56 \times 1440}{0.004899 \times 2.7183^{0.004899 \times 152}}$$

$$W_r = 9012223.6$$

The ability to emptying (the difference between the dynamic storage and the regular reserve) is:

$$\Delta W = W_0 - W_r$$

$$\Delta W = 18976909.6 - 9012223.6$$

$$\Delta W = 9964686$$

The rate of renewal (T_r) per cent and the minimum time of renewal (t_m) are calculated with the following formulas.

$$T_r = \frac{\Delta W}{W_o} \times 100$$

$$T_r = \frac{9964686}{18976909.6} \times 100$$

$$T_r = 52.51\%$$

$$t_m = \frac{W_o}{\Delta W}$$ ---------(in years)

$$t_m = \frac{18976909.6}{9964686}$$

$$t_m = 1.9(years)$$

MODEL LAYOUT AND CALCULATED RESULTS

Below is shown the EXCELL-based model and the corresponding calculated parameters for Akako Spring.

Akako Spring (SP-01)			
		UTM-EASTING	**UTM-NORTHING**
		477450	*1006250*
ROVIENCE		**LOCALITY**	**USE**
Oromiya		*Akako*	*Water Supply*
DEVELOPMENT		**EMERGENCE**	**REGIME**
Captured		*Localized*	*Perennial*
		MEASURABLE	
		yes	
Hydrogeologic Study:		Model of Maillet	Analysis of the hydrograph
Minimum Discharge	Q_{min}=	0.529	l/sec
Maximum Discharge	Q_{max}=	1.207	l/sec
Average Monitored Discharge	Q_{avg}=	0.748	l/sec
Percent of variability	**Rv=**	90.697	%
Year (Phase) 2006			
Coefficient of exhaustion	α =	0.004898922	
Duration of phase exhaustion	**t =**	152	d
Q_o Calculated	**Qo=**	1.076	l/sec
Q_t Calculated	**Q t =**	0.511	l/sec
Dynamic Storage	**Wo=**	18976.909	m^3
Regular Storage	**W_r=**	9012.223	m^3
Capacity of emptying	**ΔW=**	9964.686	m^3
Sustainable flow duration	**DTt=**	204.13	d
Recharge (renewal) rate	**Trin=**	52.51	%
Recharge Duration (time of renewal)	**trin=**	1.9	Years

Table 7-4: Model lay out and calculated values for Akako spring

7.2.3 ENTOTO SPRING

LOCATION AND ACCESSIBILITY

Entoto spring is located along the Entoto mountain range about 2.5 kms east of Gojam-Ber spring. The monitored average discharge of the spring is about 1.21 l/s. Its geographical location is represented by the UTM coordinate of 473275mE, 1003953mN with elevation of about 2840m above mean sea level. Its elevation is the same as that of Gojam-Ber spring. The road to Entoto Mariam church passes very close to the spring reservoir which is about 470m south of the spring. The spring is developed and is being used by the Addis Ababa Water and Sewerage Authority (AAWSA) for water supply purpose. The reservoir has a capacity of 50 cubic meter. The location map of the spring site is shown in fig. 7-14 below.

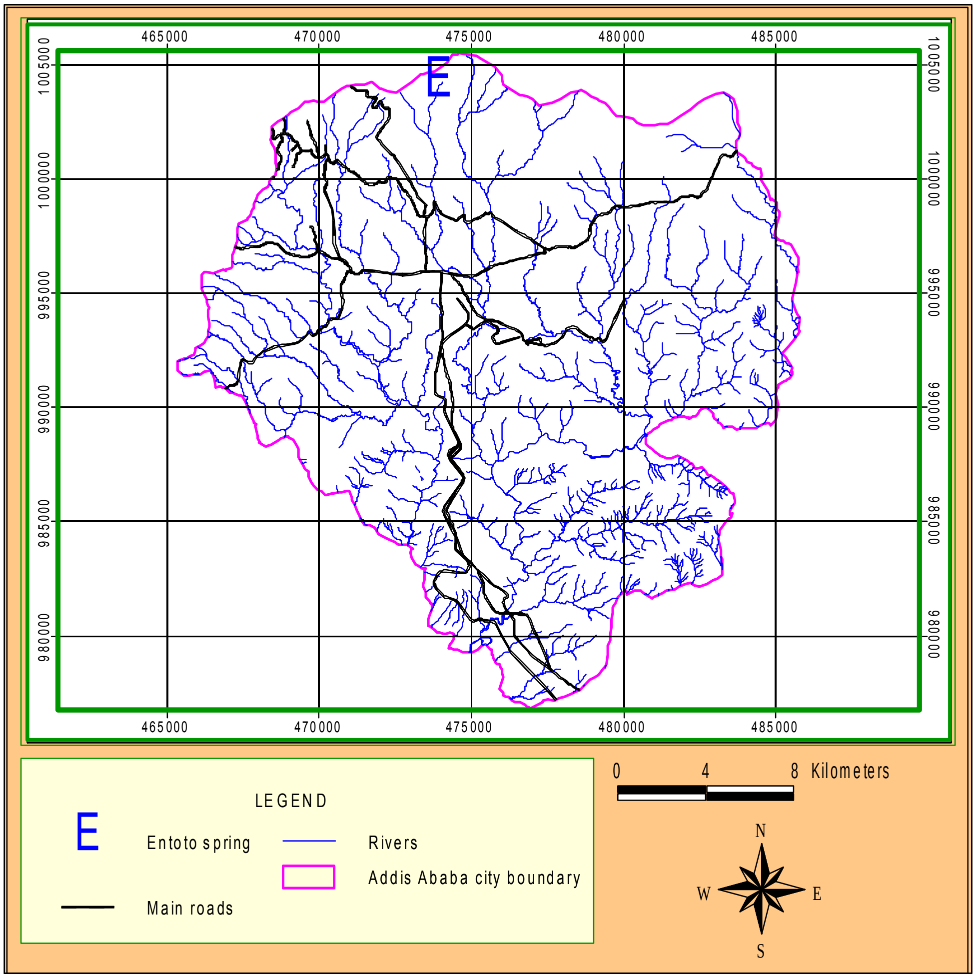


Figure 7-14: *Location map of Entoto spring*

LOCAL GEOLOGICAL AND HYDROGEOLOGICAL SETTING

Being situated at the same elevation contour as Gojam-Ber spring, the local geohydrologic conditions of the two springs are very similar. Hence rhyolites are the main rock units existing in the area. Due to their old age, the rocks have undergone intensive weathering. In addition to a N-S trending fault passing across this spring, an E-W trending fault that crosses Gojam-Ber spring also crosses this spring.

The hydraulic characteristic of the rocks is also similar to that of Gojam-Ber area spring except for the local variations as a result of the different factors such as: degree of weathering, density and/or aperture of fractures, etc. Their discharge variation can be attributed to these factors.

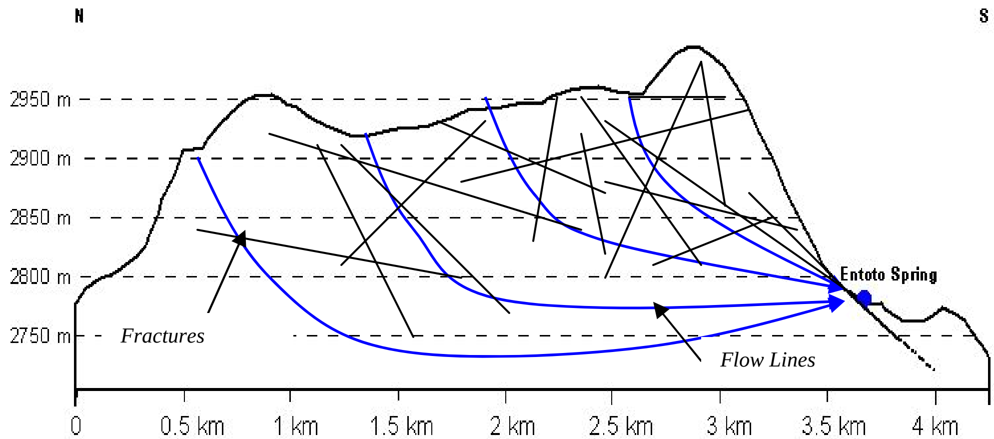


Figure 7-15: *Mode of emergence of Entoto spring*

Fig 7-16: *Entoto spring capping structure (left) and fractures on rhyolites around the spring (right)*

FLOW MODEL OF ENTOTO SPRING

The corrected exhaustion curve of this spring is as shown below.

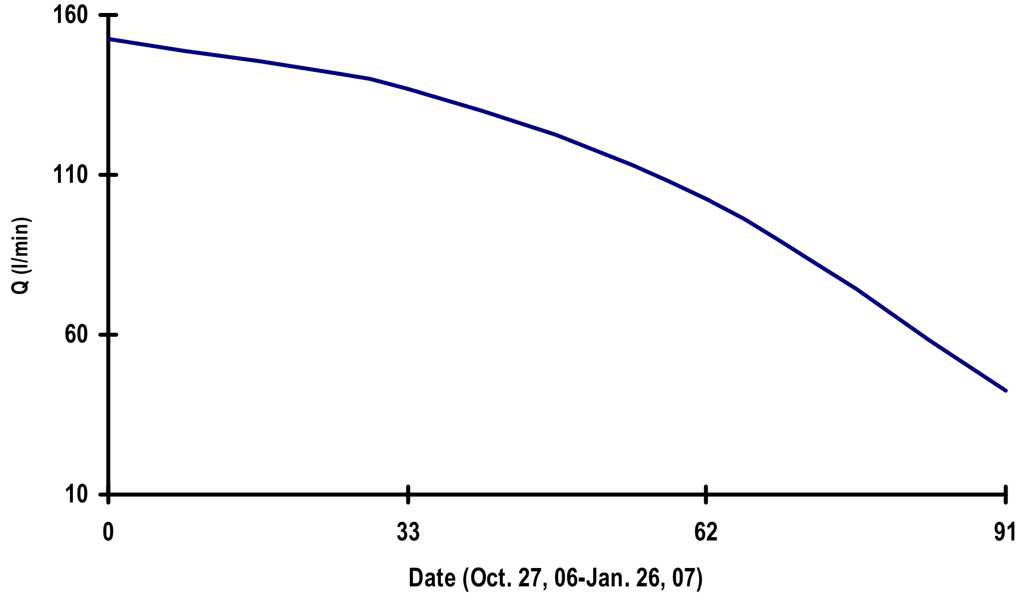


Figure 7-17: *Recession curve of Entoto spring*

Intersection of the best fit line with the Y-axis from a semi-logarithmic diagram of the above curve gives Q_{ro}.

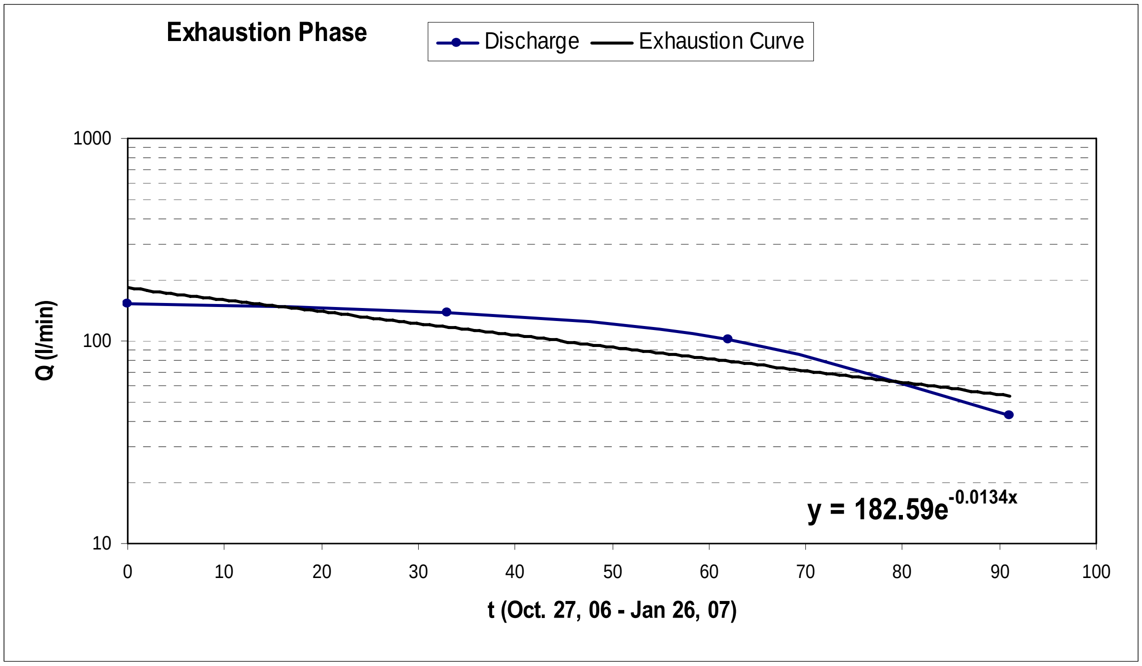


Figure 7-18: *Semi-log plot of recession curve of Entoto spring*

From the exponential equation of the exhaustion curve, α will be:

$$\alpha = \frac{(LN182.58 - LN53.94)}{91} = 0.013399$$

The corresponding expression of Maillet after inserting the calculated α values is:

$$Q_t = Q_{ro} e^{-0.013399 \quad t}$$

The curve of decrement and the corresponding equation is:

$$q_t = -30.12 \frac{(1 - 0.0122 \ t)}{(1 + \varepsilon t)}$$

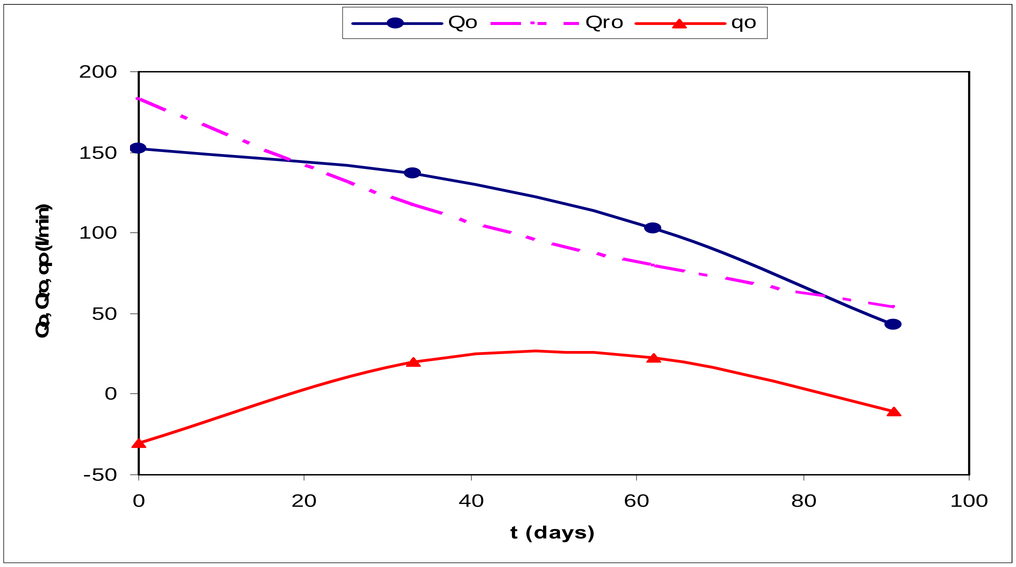


Figure 7-19: *Decrement curve of Entoto spring*

Using the equation of Mangin the value of η can be obtained from $1/t_i$.

Hence, $$\eta = \frac{1}{82}$$

$$= 0.01220$$

In the same manner as for the previous cases, knowing the value of V_i, the value of the parameter ε could have been calculated. However, due to negative qo value it becomes impractical.

The calculated values are presented in Table 7-5 below.

Spring	Q_o (l/min)	Q_{ro} (l/min)	q_o (l/min)	α	W_0 (l)	W_r (l)	ΔW (l)	T_r (%)	t_m (years)	t_i (d)	t (d)	η	ε	V_i (l)	DT_t
Entoto	152.46	182.58	-30.12	0.013399	19621887	5796899	13824998	70.46	1.42	82	91	0.01220	-	245588.2	74.63

Table 7-5: Summary of model calculated parameters for Entoto spring

WATER STORAGE

The Dynamic Storage (W_o) of the spring will be:

$$W_0 = \frac{Q_{ro}\,1440}{\alpha} \qquad \text{where: } Q_{ro} \text{ is in l/min}$$

and hence,

$$W_0 = \frac{182.58 \times 1440}{0.013399}$$

$$W_o = 19621887 \quad \text{litres}$$

The regular reserve (W_r) is determined with the following formula.

$$W_r = \frac{Q_{ro}\,1440}{\alpha e^{\alpha t}} \qquad \text{where: } Q_{ro} \text{ in l/min}$$

and hence for the spring:

$$W_r = \frac{182.58 \times 1440}{0.013399 \times 2.7183^{0.013399 \times 91}}$$

$$W_r = 5796889 \quad \text{litres}$$

The ability to emptying (the difference between the dynamic storage and the regular reserve) is:

$\Delta W = W_0 - W_r$

$\Delta W = 19621887 - 5796889$

$\Delta W = 13824998$ litres

The rate of renewal (T_r) per cent and the minimum time of renewal (t_m) are calculated with the following formulas.

$$T_r = \frac{\Delta W}{W_o} \times 100$$

$$T_r = \frac{13824998}{19621887} \times 100$$

$$T_r = 70.46 \ \%$$

$$t_m = \frac{W_o}{\Delta W} \text{ ---------(in years)}$$

$$t_m = \frac{19621887}{13824998}$$

$$t_m = 1.42 (years)$$

MODEL LAYOUT AND CALCULATED RESULTS

Below is shown the EXCELL-based model and the corresponding calculated parameters for Entoto Spring.

Entoto Spring (SP-02)		
	UTM-EASTING	**UTM-NORTHING**
	473275	*1003953*
PROVIENCE	**LOCALITY**	**USE**
Addis Ababa	*Chefe*	*Water Supply*
DEVELOPMENT	**EMERGENCE**	**REGIME**
Captured	*Localized*	*Perennial*
	MEASURABLE	
	yes	
Hydrogeologic Study:	Model of Maillet	Analysis of the hydrograph

Minimum Discharge	Q_{min}=	0.180	l/sec
Maximum Discharge	Q_{max}=	2.549	l/sec
Average Monitored Discharge	Q_{avg}=	1.207	l/sec
Percent of variability	**Rv=**	196.331	%
Year (Phase) 2006			
Coefficient of exhaustion	α =	0.013399078	
Duration of phase exhaustion	**t =**	91	d
Q_o Calculated	Q_o=	3.043	l/sec
Q_t Calculated	Q_t =	0.899	l/sec
Dynamic Storage	W_o=	19621.887	m^3
Regular Storage	W_r=	5796.889	m^3
Capacity of emptying	ΔW=	13824.998	m^3
Sustainable flow duration	DT_t=	74.63	d
Recharge (renewal) rate	T_{rin}=	70.46	%
Recharge Duration (time of renewal	t_{rin}=	1.42	Years

Table 7-6: Model lay out and calculated values for Entoto spring

7.2.4 FANTA SPRING

LOCATION AND ACCESSIBILITY

Fanta spring is located some 23 kms south of Addis Ababa. It can be accessed through the main Addis Ababa-Akaki high way and then traveling off road for about 3.5 kms in the northeast direction from Akaki town. Its geographical location is represented by the UTM coordinate of 479600mE, 981100mN at an elevation of about 2140m above mean sea level. The spring is developed and is being used by the Addis Ababa Water and Sewerage Authority (AAWSA) for water supply purpose of Akaki town. The average monitored discharge of the spring is found to be 16.6 l/s, which is the highest discharge spring so far known to be developed by AAWSA. The location map of the spring site is shown in fig. 7-20 below.

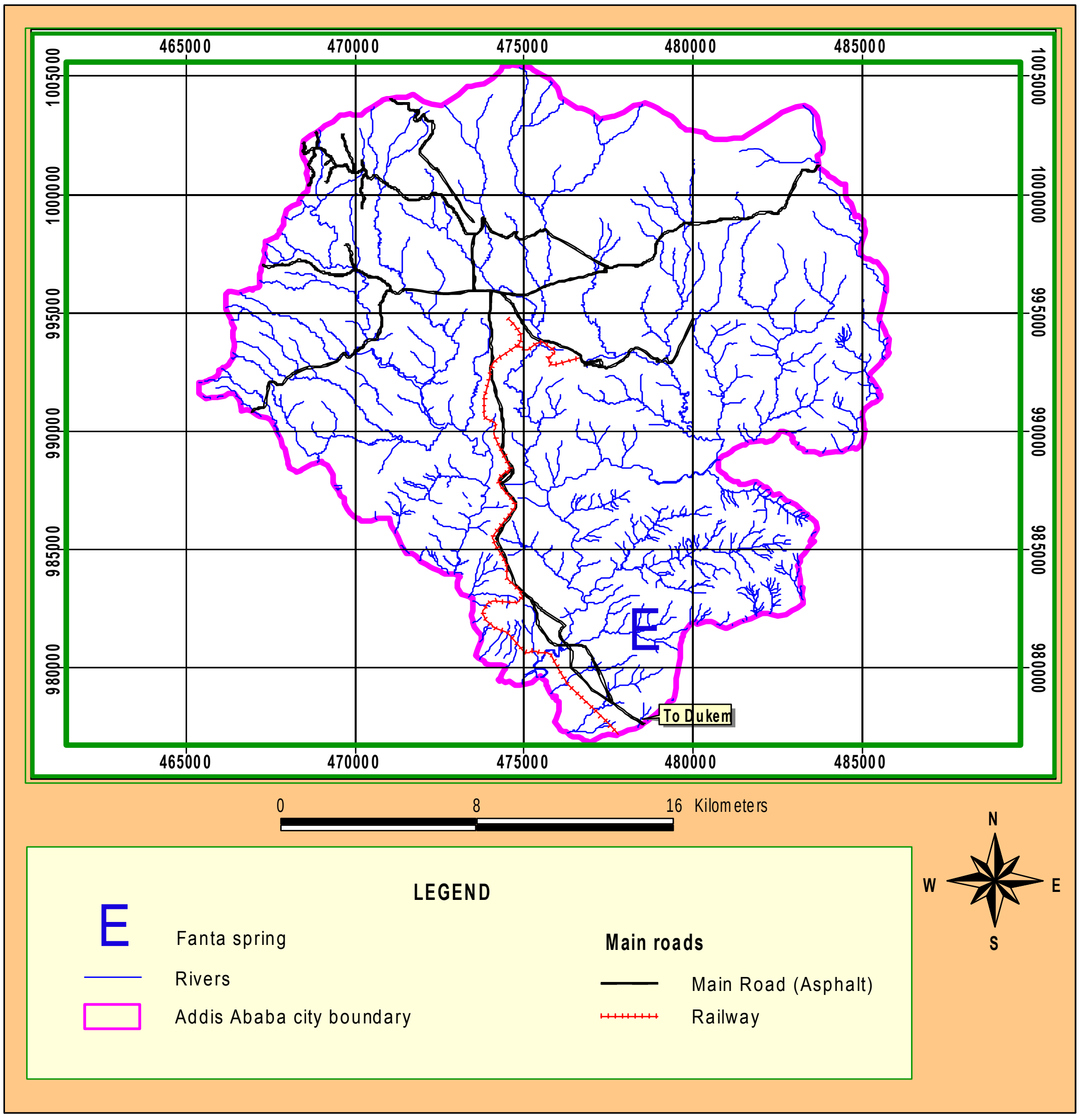


Figure 7-20: *Location map of Fanta spring*

LOCAL GEOLOGICAL AND HYDROGEOLOGICAL SETTING

Boulder forming young basalt is the main rock unit existing in the area. Vesicles are common features observed in the rocks. In the stratigraphic sequence of Addis Ababa, these rocks lie on top representing the youngest rock unit. Due to their young age, the rocks are not significantly affected by weathering. As a result fracture net works are open from which the rocks acquire their highly conductive nature. The porous (vesicular) nature of the rocks also makes them favorable from hydrogeological point of view. Apart from the existence of extensive faults, the density of fractures is higher in the area which contributes to their interconnection and considerable hydrogeological suitability. The suitable hydrogeological nature of the rocks can be explained by the high productivity of the Akaki well field, which is about 3.5 kms south west of Fanta spring in a similar geohydrological setting. The area in general is composed of basaltic rocks of different textures (fractured olivine basalt, scoria, vesicular basalt and scoriaceous basalt). Despite this, they seem to behave as a single unit hydrogeologically. The emergence of the spring is along a fault line from the fracture reservoir of the young volcanics (fig. 7-21)

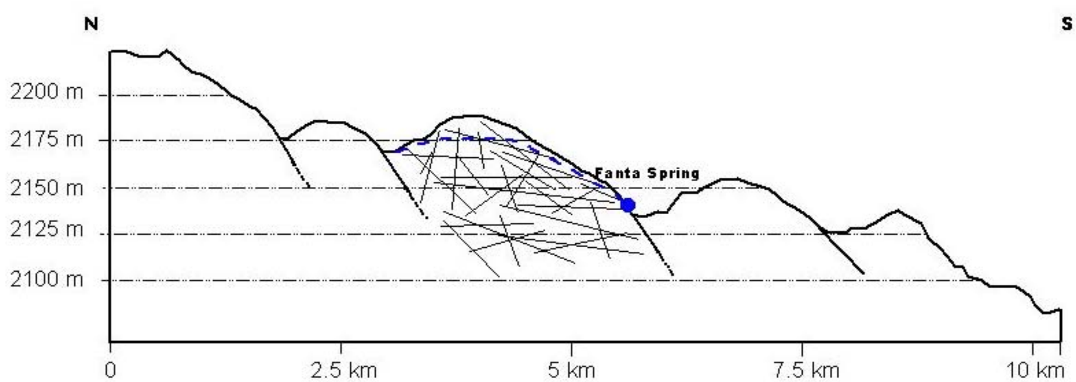


Figure 7-21: *Mode of emergence of Fanta spring*

Fig 7-22: *Vesiculated basaltic boulders around Fanta spring (left) and chlorination tank of the spring.*

FLOW MODEL OF FANTA SPRING

The corrected exhaustion curve of this spring is as shown below.

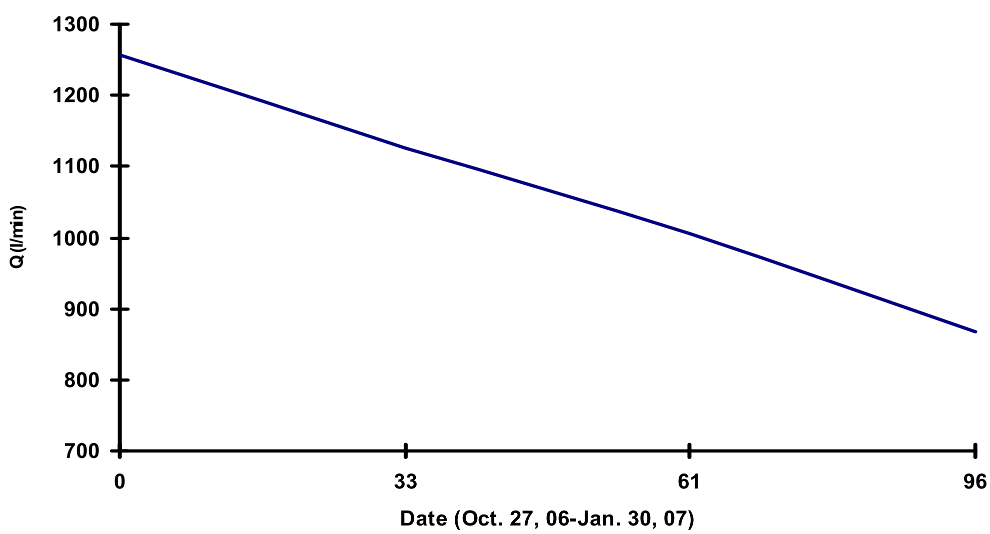


Figure 7-23: *Recession curve of Fanta spring*

Intersection of the best fit line with the Y-axis from a semi-logarithmic diagram of the above curve gives Q_{ro}.

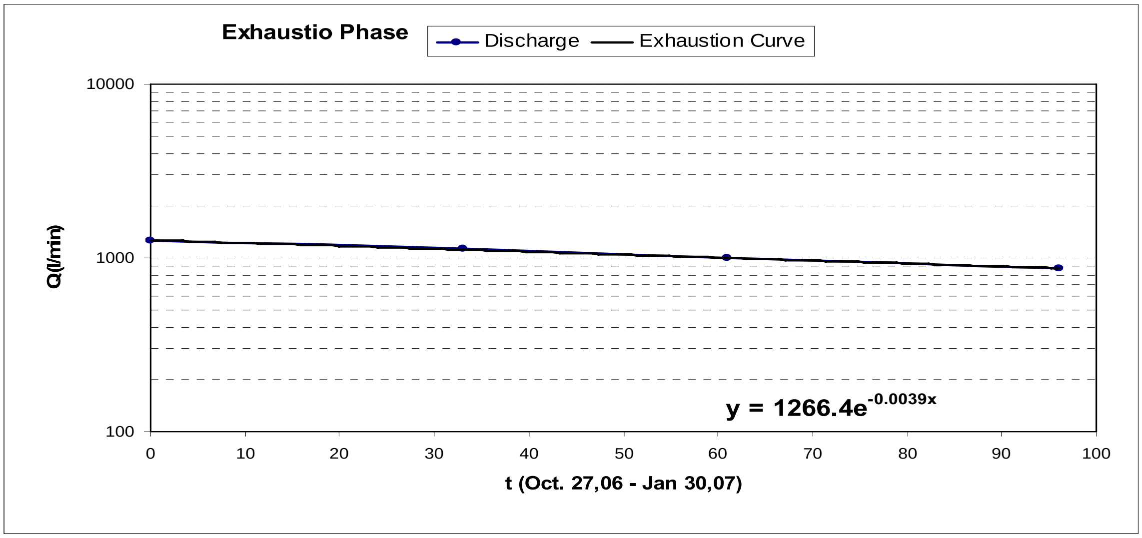


Figure 7-24: *Semi-log plot of recession curve of Entoto spring*

From the exponential equation of the exhaustion curve, α will be:

$$\alpha = \frac{(LN1266.42 - LN870.9)}{96} = 0.003900$$

The corresponding expression of Maillet after inserting the calculated α values is:

$$Q_t = Q_{ro} e^{-0.003900 \quad t}$$

The curve of decrement and the corresponding equation is:

$$q_t = -10.38 \frac{(1 - 0.01042 \quad t)}{(1 + \varepsilon t)}$$

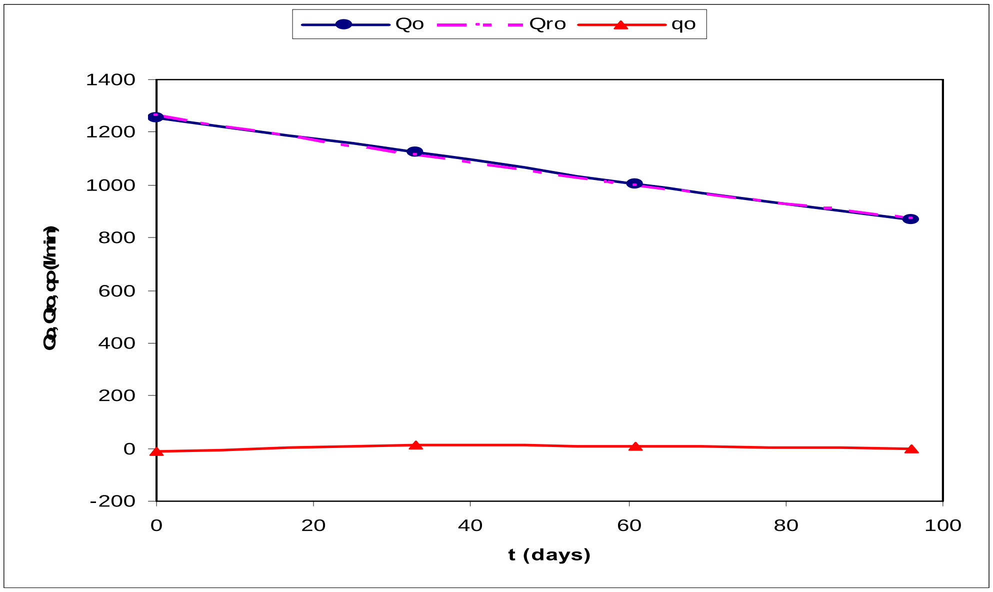


Figure 7-25: *Decrement curve of Fanta spring*

Using the equation of Mangin the value of η can be obtained from $1/t_i$.

Hence,

$$\eta = \frac{1}{96}$$

$$= 0.01042$$

In the same manner as for Entoto spring the calculation of the parameter ε was not possible.

The calculated values are presented in Table 7-7 below.

Spring	Q_o (l/min)	Q_{ro} (l/min)	q_o (l/min)	α	W_0 (l)	W_r (l)	ΔW (l)	T_r (%)	t_m (years)	t_i (d)	t (d)	η	ε	V_i (l)	DT_t
Fanta	1256.04	1266.42	-10.38	0.003900	467573579	321543256	146030320.3	31.23	3.20	96	96	0.01042	-	103821.73	256.39

Table 7-7: Summary of model calculated parameters for Fanta spring

WATER STORAGE

The Dynamic Storage (W_o) of the spring will be:

$$W_0 = \frac{Q_{ro}1440}{\alpha}$$ where: Q_{ro} is in l/min

$$W_0 = \frac{1266.42 \times 1440}{0.003900}$$

$$W_o = 467573579$$

The regular reserve (W_r) is determined with the following formula.

$$W_r = \frac{Q_{ro}1440}{\alpha e^{\alpha t}}$$ where: Q_{ro} in l/min

$$W_r = \frac{1266.42 \times 1440}{0.003900 \times 2.7183^{0.003900 \times 96}}$$

$$W_r = 321543256$$

The ability to emptying (the difference between the dynamic storage and the regular reserve) is:

$\Delta W = W_0 - W_r$

$\Delta W = 467573579 - 321543256$

$\Delta W = 146030320.3$

The rate of renewal (T_r) percent and the minimum time of renewal (t_m) are calculated with the following formulae.

$$T_r = \frac{\Delta W}{W_o} \times 100$$

$$T_r = \frac{146030320.3}{467573579} \times 100$$

$$T_r = 31.23 \ \%$$

$$t_m = \frac{W_o}{\Delta W} \text{ ---------(in years)}$$

$$t_m = \frac{467573579}{146030320.3}$$

$$t_m = 3.2(years)$$

MODEL LAYOUT AND CALCULATED RESULTS

Below is shown the EXCELL-based model and the corresponding calculated parameters for Fanta Spring.

Fanta Spring (SP-05)			
		UTM-EASTING	**UTM-NORTHING**
		479600	*981100*
PROVIENCE		**LOCALITY**	**USE**
Addis Ababa		*Fanta*	*Water Supply*
DEVELOPMENT		**EMERGENCE**	**REGIME**
Captured		*Localized*	*Perennial*
		MEASURABLE	
		yes	
Hydrogeologic Study:		Model of Maillet	Analysis of the hydrograph
Minimum Discharge	Q_{min}=	14.461	l/sec
Maximum Discharge	Q_{max}=	20.934	l/sec
Average Monitored Discharge	Q_{avg}=	16.608	l/sec
Percent of variability	**Rv=**	38.976	%

Year (Phase) 2006			
Coefficient of exhaustion	α =	0.003900231	
Duration of phase exhaustion	t =	96	d
Q_o Calculated	Q_o=	21.107	l/sec
Q_t Calculated	Q_t =	14.515	l/sec
Dynamic Storage	W_o=	467573.579	m^3
Regular Storage	W_r=	321543.256	m^3
Capacity of emptying	ΔW=	146030.323	m^3
Sustainable flow duration	DT_t=	256.39	d
Recharge (renewal) rate	T_{rin}=	31.23	%
Recharge Duration (time of renewal)	t_{rin}=	3.20	Years

Table 7-8: Model lay out and calculated values for Fanta spring

7.2.5 RAS MEKONNEN

LOCATION AND ACCESSIBILITY

Ras Mekonnen spring is located south of Intoto mountain towards the central part of the city around Arat Kilo. It along the road from Arat Kilo to Pizza at a place called Ras Mekonnen Bridge. Its geographical location is represented by the UTM coordinate of 473262mE, 999303mN at an elevation of about 2465m above mean sea level. The spring is by the City Municipality and has long been used as a fountain. The average monitored discharge of the spring is about 0.44 l/s. The location map of the spring site is shown in fig. 7-24 below.

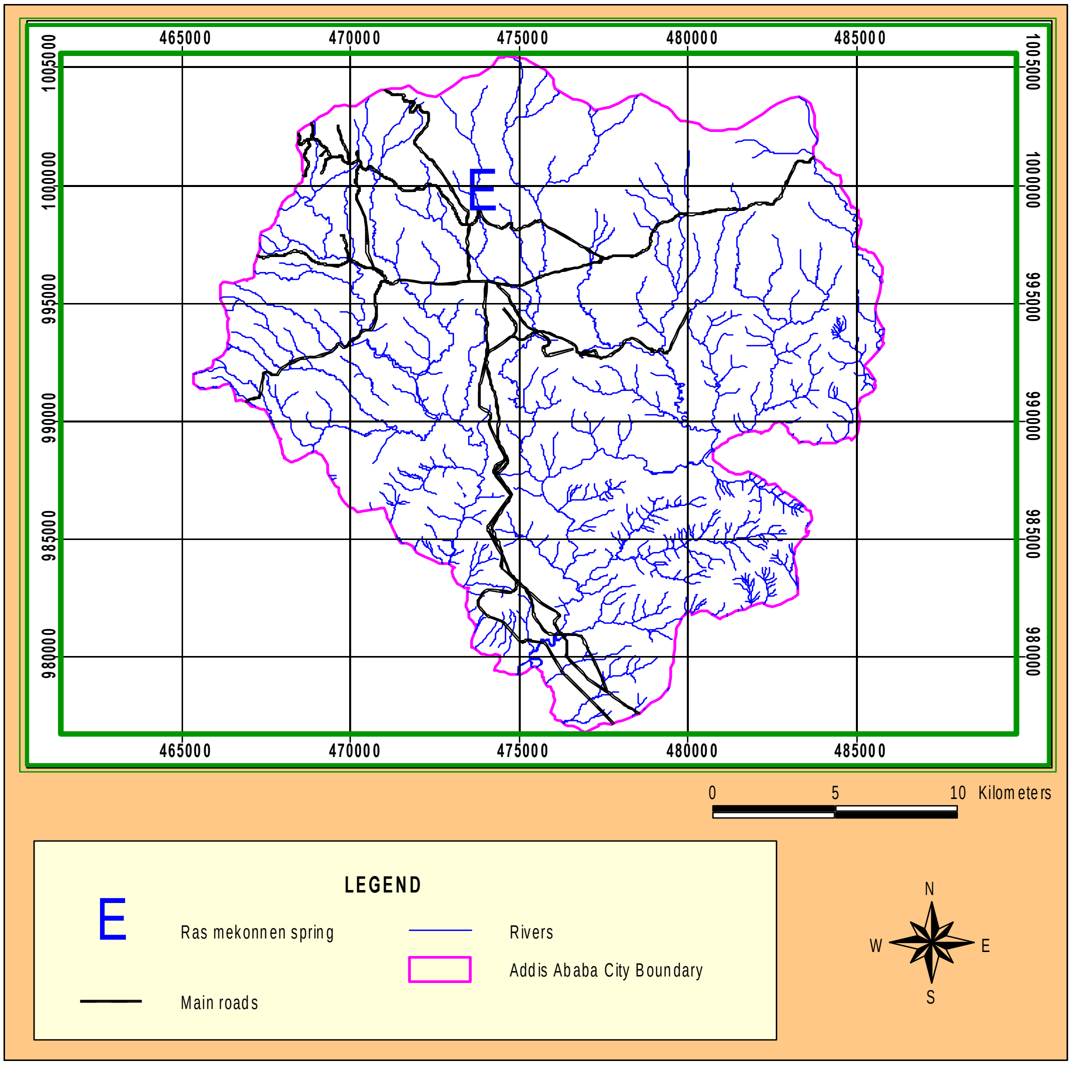


Figure 7-26: *Location map of Ras Mekonnen spring*

LOCAL GEOLOGICAL AND HYDROGEOLOGICAL SETTING

Old basalt (Addis Ababa basalt) that overlies the Intoto silicics is the main rock units existing in the area. As described earlier in Chapter 3, this basalt unit is olivine porphyritic and plagioclase porphyritic type (Morton, 1974; Varnier et al., 1985). The one that outcrops around Ras Mekonnen spring is the olivine porphyritic basalt. The spring seems to emerge as a result of a N-S trending fault that extends far from around Entoto and goes past the spring. Besides, the flow of the river closer to this spring seems to be controlled by this fault.

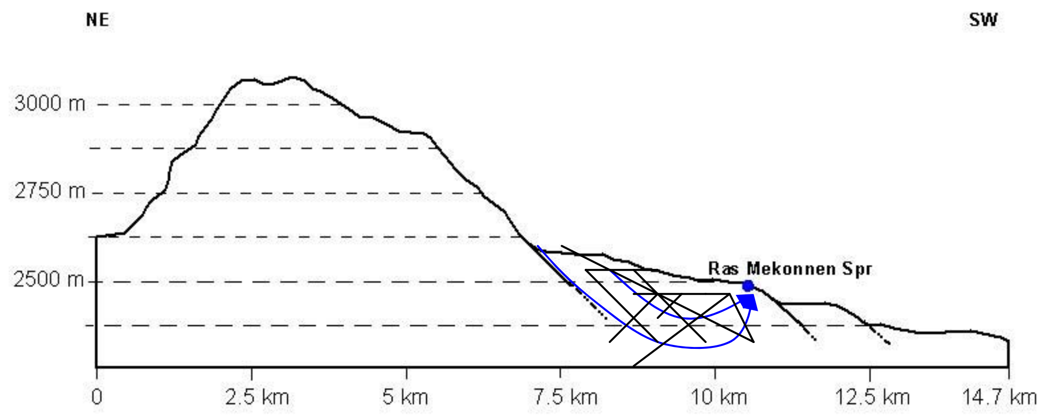


Figure 7-27: *Mode of emergence of Ras Mekonnen spring*

Figure 7-28: *Ras Mekonnen spring (built as fountain)*

FLOW MODEL OF RAS MEKONNEN SPRING

The corrected exhaustion curve of this spring is as shown below.

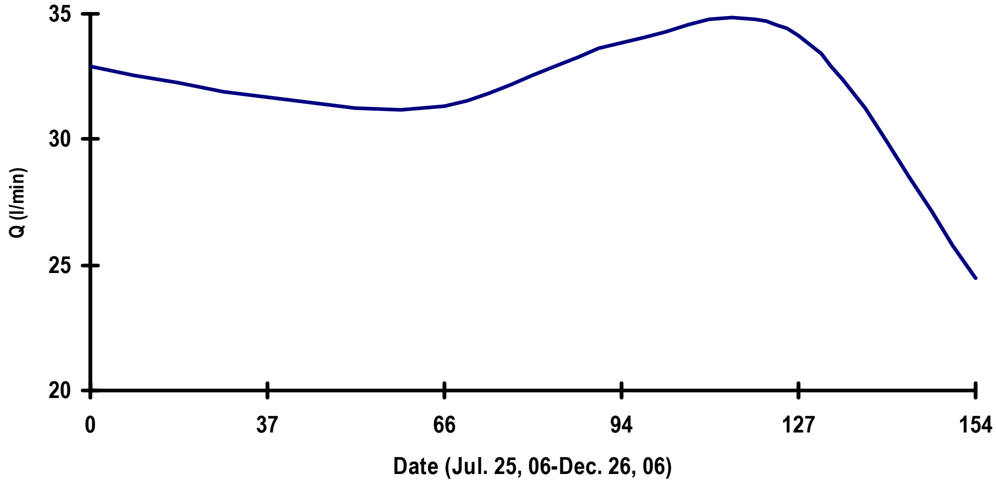


Figure 7-29: *Recession curve of Ras Mekonnen spring*

Intersection of the best fit line with the Y-axis from a semi-logarithmic diagram of the above curve gives Q_{ro}.

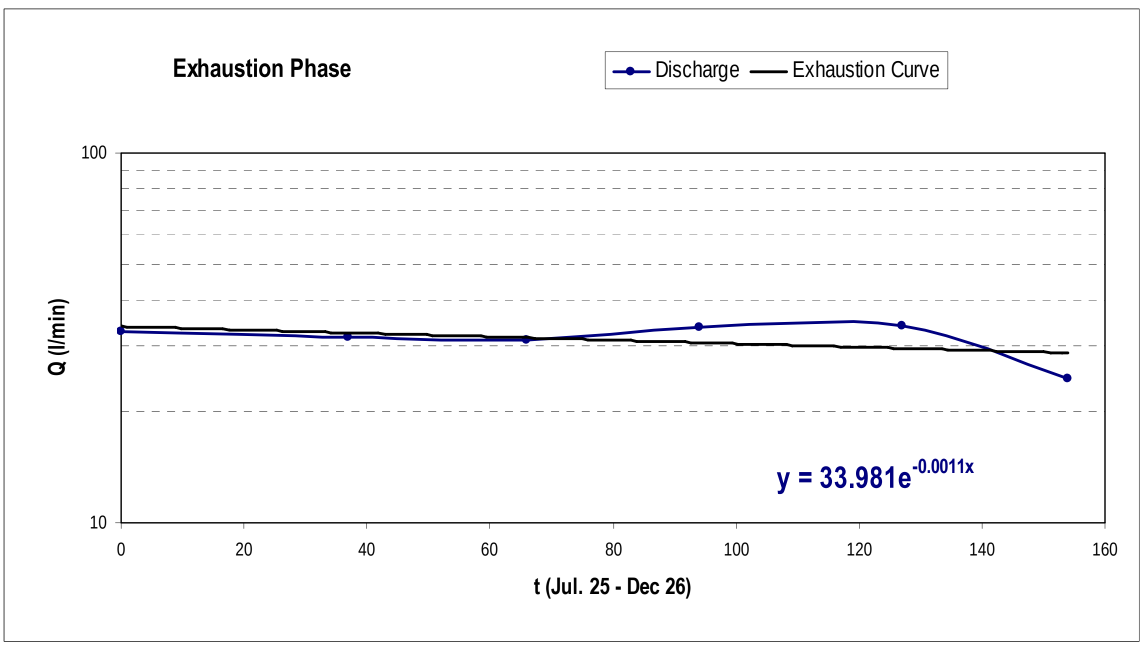


Figure 7-30: *Semi-log plot of recession curve of Ras Mekonnen spring*

From the exponential equation of the exhaustion curve, α will be:

$$\alpha = \frac{(LN33.96 - LN28.68)}{154} = 0.001097$$

The corresponding expression of Maillet after inserting the calculated α values is:

$$Q_t = Q_{ro} e^{-0.001097\ t}$$

The curve of decrement and the corresponding equation is:

$$q_t = -1.08 \frac{(1 - 0.00709\ t)}{(1 + \varepsilon t)}$$

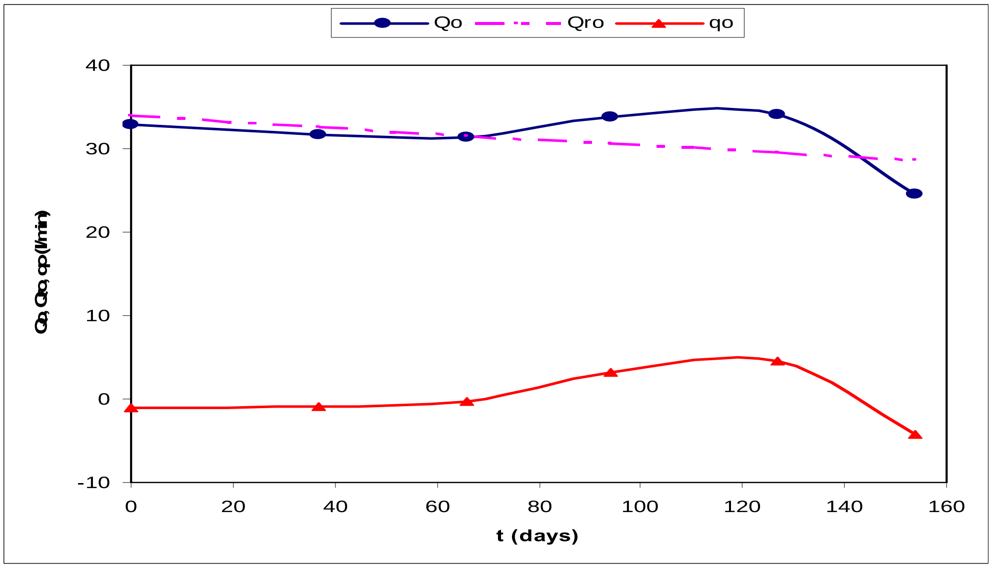


Figure 7-31: *Decrememt curve of Ras Mekonnen spring*

Using the equation of Mangin the value of η can be obtained from $1/t_i$.

Hence, $$\eta = \frac{1}{63}$$

$$= 0.01587$$

For the same reason as for the previous two springs, parameter ε can not be calculated.

The calculated values are presented in Table 7-9 below.

Spring	Q_o (l/min)	Q_{ro} (l/min)	q_o (l/min)	α	W_0 (l)	W_r (l)	ΔW (l)	T_r (%)	t_m (years)	t_i (d)	t (d)	η	ε	V_i (l)	DT_t
Ras Mekonnen	32.88	33.96	-1.08	0.001097	44566342	37637257	6929085.3	15.54	6.43	63	154	0.01587	-	26641.14	911.33

Table 7-9: Summary of model calculated parameters for Ras Mekonnen spring

WATER STORAGE

The Dynamic Storage (W_o) of the spring will be:

$$W_0 = \frac{Q_{ro}\,1440}{\alpha} \qquad \text{where: } Q_{ro} \text{ is in l/min}$$

$$W_0 = \frac{33.96 \times 1440}{0.001097}$$

$$W_o = 44566342$$

The regular reserve (W_r) is determined with the following formula.

$$W_r = \frac{Q_{ro}\,1440}{\alpha e^{\alpha t}} \qquad \text{where: } Q_{ro} \text{ in l/min}$$

$$W_r = \frac{33.96 \times 1440}{0.001097 \times 2.7183^{0.001097 \times 154}}$$

$$W_r = 37637257$$

The ability to emptying (the difference between the dynamic storage and the regular reserve) is:

$$\Delta W = W_0 - W_r$$

$$\Delta W = 44566342 - 37637257$$

$$\Delta W = 6929085$$

The rate of renewal (T_r) per cent and the minimum time of renewal (t_m) are calculated with the following formulae.

$$T_r = \frac{\Delta W}{W_o} \times 100$$

$$T_r = \frac{6929085}{44566342} \times 100$$

$$T_r = 15.55\ \%$$

$$t_m = \frac{W_o}{\Delta W} \text{ ---------(in years)}$$

$$t_m = \frac{44566342}{6929085}$$

$$t_m = 6.43(years)$$

MODEL LAYOUT AND CALCULATED RESULTS

Below is shown the EXCELL-based model and the corresponding calculated parameters for Ras Mekonnen Spring.

Ras Mekonnen Spring (SP-04)		
	UTM-EASTING	**UTM-NORTHING**
	473262	*999303*
PROVIENCE	**LOCALITY**	**USE**
Adddis Ababa	*Ras Mekonnen Bridge*	*Fountain*
DEVELOPMENT	**EMERGENCE**	**REGIME**
Captured	*Localized*	*Perennial*
	MEASURABLE	
	yes	
Hydrogeologic Study:	Model of Maillet	Analysis of the hydrograph

Minimum Discharge	Q_{min}=	0.170	l/sec
Maximum Discharge	Q_{max}=	0.569	l/sec
Average Monitored Discharge	Q_{avg}=	0.438	l/sec
Percent of variability	**Rv=**	91.075	%
Year (Phase) 2006			
Coefficient of exhaustion	α =	0.001097294	
Duration of phase exhaustion	**t** =	154	d
Q_o **Calculated**	Q_o=	0.566	l/sec
Q_t **Calculated**	Q_t =	0.478	l/sec
Dynamic Storage	W_o=	44566.342	m^3
Regular Reserve	W_r=	37637.257	m^3
Capacity of emptying	ΔW=	6929.085	m^3
Sustainable flow duration	DT_t=	911.33	d
Recharge (renewal) rate	T_{rin}=	15.55	%
Recharge Duration (time of renewal)	t_{rin}=	6.43	Years

Table 7-10: Model lay out and calculated values for Ras Mekonnen spring

7.3 SUMMARY OF MODEL RESULTS

A summary of the calculated parameters that govern the spring flow are presented in Table 7-11 below. A brief discussion on the tabulated quantitative results are also given for which the meaning and explanation is given in the conclusion part.

- Generally, springs for which the coefficient of heterogeneity of the outflow (ε) are calculated (Gojam-Ber and Akako), the values are nearer to zero. This parameter is not calculated for the rest of springs due to a negative q_o value.
- The exhaustion coefficients (α) calculated for the springs have small values ranging between (0.001-0.004).
- Negative q_o values have been obtained in three of the springs (Entoto, Fanta and Ras Mekonnen).
- The current flow (discharge) of springs and the issue of sustainable flow are independent of each other. Sustainability is rather dependent on their storage of capacities. This means that high discharge does not necessarily imply a sustained flow and vice versa. If springs of low reserve are compensated by high renewal rate, they can sustainably flow for long time. On the contrary, if springs of low renewal rate are compensated by big reserves, a sustained flow can be ensured.
- Infiltrated volume (V_i) is bigger for springs with high renewal rate and vice versa.

Spring	Q_o (l/min)	Q_{ro} (l/min)	q_o (l/min)	A	W_0 (l)	W_r (l)	ΔW (l)	T_r (%)	t_m (years)	t_i (days)	t (days)	η	ε	V_i (l)	DTt
Gojam-Ber	**82.2**	**75.12**	**7.08**	**0.001998**	54131536	42760387	11371149	21.01	4.76	**40**	**118**	0.02500	0.52	43921.28	500.42
Akako	**71.58**	**64.56**	**7.02**	**0.004899**	18976909.6	9012223.6	9964686	52.51	1.90	**62**	**152**	0.01613	0.22	86782	204.13
Entoto	**152.46**	**182.58**	**-30.12**	**0.013399**	19621887	5796889	13824998	70.46	1.42	**82**	**91**	0.01220	-	245588.2	74.63
Fanta	**1256.04**	**1266.42**	**-10.38**	**0.003900**	4677573579	321543256	146030320.3	31.23	3.20	**96**	**96**	0.01042	-	103821.73	256.39
Ras Mekonnen	**32.88**	**33.96**	**-1.08**	**0.001097**	44566342	37637257	6929085.3	15.55	6.43	**63**	**154**	0.01587	-	26641.14	911.33

Table 7-11: Summary of model calculated parameters for all springs

- The spring sources for which the replenishment rates have been calculated, the importance of the regular reservoirs varied from negligible to average, while the discharge controlling capacity of the aquifer varied from acceptable to nearly null (Table7-12). From the table it can be observed that 15 to 70% of the outflows have been renewed in the course of the year.

Rate of renewal (replenishment)		Importance of the regular reservoirs	Discharge controlling capacity of the aquifer	
			Annual	Time unlimited
~100%-50%	70.46 % (Entoto) 52.51% (Akako)	negligible	null	null
~50%-10%	31.23% (Fanta) 21.00% (Gojam-Ber) 15.54% (Ras Mekonnen)	Average	acceptable	limited
~10%	-	High	Optimal	Optimal
<10%	-	Very high	Very high	Very high

Table 7-12: Application of the rate renewal (modified from Celico, 1988).

- It has also been tried to establish a relationship between the renewal rates and Tritium concentrations (fig. 7-32). They tend to show very similar pattern indicating that both of them are related to residence times and if this modeling can be supported by isotope studies, results can become more and more justified.

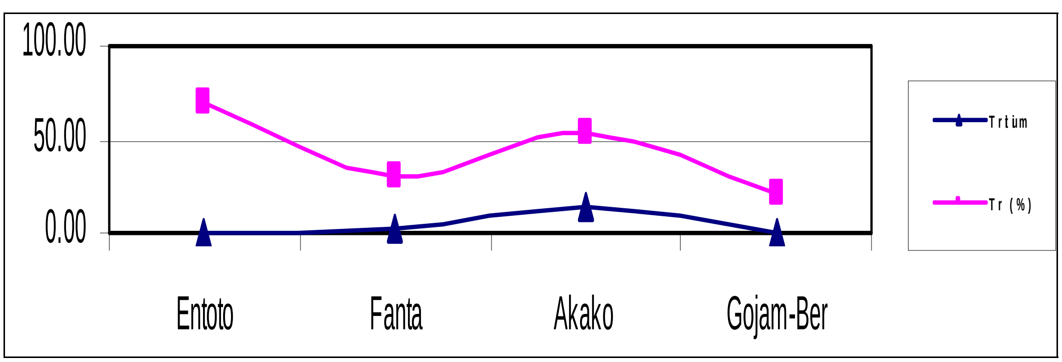


Figure 7-32: A plot of infiltration rate versus tritium values.

CHAPTER EIGHT

SYNTHESIS

All the chapters that have been discussed earlier are directly or indirectly related to the core subject matter of the thesis (spring modeling). The objective of modeling a spring source is one way of understanding the system and the factors that affect it. Therefore, natural phenomena that are thought to be linked in any way with the spring flow have to be taken in to consideration. The effects of these factors may not be independently linked to the spring sources but also with each other. Therefore, this section deals with the relevance of each of the chapters discussed so far with the objective of the study.

The supply of naturally occurring solid reactants is ultimately controlled by geologic processes. Elements not available in the rock minerals contacted by the water cannot be expected to be present in the final solution. The importance of rock composition, however, is only among the many factors. The purity and crystal size of minerals, the rock texture and porosity, the regional structure, the degree of fissuring, the length of previous exposure time, and a good number of other factors might influence the composition of water passing over and through the rock.

Air in soil interstices is commonly l0-100 times richer in CO_2 than ordinary air (Bolt and Bruggenwert, 1978, p. 11). Water moving through soil dissolves some of this CO_2, and the H^+, HCO_3^-, and CO_3^{2-} ions are potent forces in controlling the pH of the water and in attacking rock minerals.

It is already discussed that Addis Ababa is covered by a variety of volcanic rocks. Despite their similarity in the fact that they are the products of volcanism, they behave differently in response to a given stress (such as weathering, erosion, tectonics, etc) due to their difference in their genesis. Some of them are thrown to the air by explosion to form a volcanic pyroclastic rock when they fall back to the surface. Others flow on the surface to form piles of lava flow which later solidify and become a rock. Even after their formation, rocks can be weathered and/or transported to other places thereby changing their form and stand as a distinct unit. This difference in genetic origin of the rocks resulted in spatial heterogeneity both on the surface and beneath. Besides the rocks have been formed at different times hence young and old rocks would have different properties due to their difference in age. Therefore rock properties can vary spatially and temporally as a result of the genesis of the rocks and due to the action of geological processes.

Tectonic structures are also responsible for the occurrence, distribution and movement of groundwater. Addis Ababa, being located at the western shoulder of the main Ethiopian rift, it is a place where numerous tectonic structures can be found.

In general, lateral and vertical heterogeneities of the geologic formations can be attributed to the genesis of the rocks, the geological/gochemical processes that took place, the mineral composition of the rocks and the tectonic history of the area. Heterogeneity on the other hand is an important control for the occurrence, distribution and movement of groundwater. This in other words would mean that geology controls the existence, yield, recharge, chemical composition and storage conditions, etc of a spring source.

The supply of liquid water from groundwater is replenished by precipitation. Obviously, amount and rate of rainfall, runoff, and evaporation are important factors in the control of natural-water composition. Hence, spatial and temporal variation in rain fall can result in variation of spring discharge and chemical composition. Variation in rainfall in turn is dependent on different climatologic factors prevailing in the area. Thus, the study of a spring source should take in to consideration climatologic elements in the area.

An area can be categorized under a given climatologic zone based on its elevation. Accordingly, five climatic zones (Kur, Dega, Woinadega, Kola and Bereha) have been defined in Ethiopia by the National Atlas of Ethiopia. Depending on the climatic zone to which it belongs, an area receives mean annual rainfall different from the other. For instance, Addis Ababa falls in the Woinadega climatic zone receiving mean annual rainfall of 1123mm. This gives an idea about the suitability of the area for potential recharge.

Climates characterized by alternating wet and dry seasons may favor weathering reactions that produce considerably larger amounts of soluble inorganic matter at some seasons of the year than at other seasons. The influence of climate on water quality may thus be displayed not only in amounts and kinds of solute ions, but also in the annual regime of water-quality fluctuation.

A changing trend of temperature would imply a changing trend of the extent of evaporation. A changing trend of evaporation on the other hand would imply a changing trend of infiltration volume. Therefore, temperature can be correlated directly to evaporation and inversely to volume of infiltration.

The duration during which the daily sun shine lasts can affect the amount of water that should be lost by evaporation. The longer the duration of sunshine hours, the higher will be the rate of evaporation loss giving rise to a direct relationship between the two.

In conclusion, the amount and distribution of rainfall can be substantially affected by alteration of one or more of the meteorological elements mentioned. Had this not been the case, the discharge of springs would have been consistent while seasons change. For instance, a long drought period is characterized by long sun shine hours, high temperature and low relative humidity with little or no rain fall. In such cases, a spring source that is fed by rain fall would suffer a considerable discharge decline.

Observations of seasonal changes in water chemistry revealed that precipitation has significant contribution on the discharge of the springs. Besides isotopic signatures of water samples have also been analysed for comparison of residence times.

The different volcanic rocks that cover Addis Ababa area have variable hydraulic properties. These properties in turn, are related to the geological processes during and after the formation of the rocks. Original hydraulic properties of geological formations can be later modified by other processes like weathering, tectonics and hydrothermal activity.

During the early stage of weathering (like the weathered parts of the young volcanic rocks covering the southern parts of Addis Ababa), the secondary permeability, due to weathering zones is very high. Then it tends to decrease at the latter stage of weathering due to the formation of significant amounts of clay fractions (like the old acidic rocks of Entoto). As the weathering process continues almost all permeability due to primary porosity might be masked. As a result a variation in the hydraulic properties of the rocks will result due to weathering.

Groundwater circulation and storage in volcanic rocks depend on the type of porosity and permeability formed during and after the rock formation. Rocks possessing primary porosity may not necessarily give rise to primary permeability unless the primary porosities are interconnected by means of fracturing to produce secondary permeability. The tectonic history of Addis Ababa is closely related to the development of the Main Ethiopian Rift that has developed faulting and fracturing of the rocks. Consequently, groundwater storage and flow is highly controlled by secondary porosity and permeability. This is a modification of the hydraulic properties of the rocks due to tectonic activity.

Deep circulating hot water has a tendency of dissolving mineral components of the rock through which it flows. As a result rocks in contact with the water will be altered loosing their original hydraulic properties. According to Tamiru Alemayehu, 2006 filwoha is one the well known thermal springs in Addis Ababa. It is thought to be controlled by deep seated fault which is older than 5Ma, with heat source probably induced from the near by volcanic center located west and east of Addis Ababa.

CHAPTER NINE

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

- ✓ Different sized rain events produce notably different peak shapes.
- ✓ The value of the coefficient of heterogeneity of the outflow (ε) nearness to zero indicates that the processes of infiltration and emptying in the studied volcanic rocks are slow. It can be taken as an indication that infiltration occurs on a net of less interconnected fractures providing their contribution to the saturated zone of the hydrogeologic system independently (Civita & Vigna, 1985). Still a very small value (0.22) is obtained for Akako spring implying that fracture interconnection towards the peak of the Intoto mountain is comparatively less.
- ✓ Small α values represent, Celico (1988):
  - ➢ low total permeability of the water-bearing zone;
  - ➢ long times of infiltration towards the stratum;
  - ➢ presence of a water-bearing zone with great water volumes of dynamic storage (especially as for Entoto, Fanta and Ras Mekonnen);
  - ➢ slow emptying.
- ✓ Negative q_o values for three springs (Entoto, Fanta and Ras Mekonnen) would mean that the recession coefficient (α) increases with time indicating the existence of higher degree of aquifer heterogeneity that gave rise to a bulging out curve. For such springs the out flow through the more conductive zone will be much quicker

than that of less conductive zone. This will result in an increased discharge some time after recession has begun (Ognjen Bonacci, 1993). The cases of Entoto and Ras Mekonnen springs, for instance, can be related to this explanation as their catchments might be composed of formations of variable conductivities due to differential weathering, fracturing and existence of lithologies of different ages (rhyolite and basalt). Artificial factors such as pumping might also be responsible for such an increase of discharge after recession starts. A newly developed well field close to Fanta spring has been intermittently functioning during the period of monitoring which might have affected the curve.

- ✓ Small coefficient of infiltration, η ($1/t_i$), would mean the contribution of infiltrating water to spring discharge lasts longer than those with high η values.

- ✓ Generally springs of the central and southern parts have reserves high enough for sustainable flow. According to the model output, Ras Mekonnen spring has the maximum reserve currently in the basin that ensures a sustainable flow of 911 days. On the other hand springs of the northern part have relatively lower reserves with the exception of Gojam-Ber spring. Entoto spring has the lowest reserve in the hydrogeologic basin that would last for about 75 days. However, this spring has got the highest renewal rate of 70.46% that can compensate for the low reserve. On the contrary, Ras Mekonnen spring has the least renewal rate (15.54%). This might be attributed to the existence of large part of the spring catchment within the built-up area of the city, which favours runoff than infiltration.

- ✓ Infiltration rate for Fanta spring is lower (31.23%) as compared to Akako (52.51%) and Entoto (70.46%). This can be explained by the flat topography which favours high volume of infiltration and thick black cotton soil that causes low infiltration rate for Fanta spring. On the other hand the other two springs lie on a steep slope that justifies low infiltration volume and lateritic soil cover favouring higher infiltration rate.

- ✓ Entoto and Ras Mekonnen springs have observed to possess the maximum and minimum infiltrated volumes (V_i) respectively.

- ✓ Relatively big volumes of water are infiltrated in Entoto and Fanta springs indicating that they might cover wide physiographic basin.

- ✓ Recession curves are influenced by geology and geometry of the flow system supporting the spring.

- ✓ If spring discharge occurs from several sources or geologically diverse settings, that the recession curve slopes may change accordingly.

- ✓ Springs discharging perennially without significant variation in discharge, despite long term drought conditions, indicate at least partial connection to a deeper flow path with a more distant source of recharge and subsequent longer residence time than springs exhibiting large fluctuations in discharge rates. The combination of both decreased flow but continuous discharge at a single spring outlet suggests a mixed deep and shallow source (Gentry et.al, 2004). Moderate to high discharge fluctuations have been observed in the studied springs indicateing that they represent mixed to shallow sources.

- ✓ Several possible explanations exist for the lag between rainfall events and an increase in spring discharge. The lag may represent the time it takes for: (1) rainfall infiltration in the unsaturated zone in the vicinity of the spring to reach the spring orifice; (2) a recharge pulse to reach the springhead from a specific fracture set in the unconfined shallow aquifer; or (3) the hydraulic pressure change response to propagate through the deep bedrock aquifer from the zone of recharge to the springhead. In the cases of the studied springs it is believed that any one or a combination of the mentioned factors are responsible for the lag.

RECOMMENDATIONS

- ✓ Many parts of Ethiopia including Addis Ababa are characterized by widely separated (non overlaping) rainfall events suitable for the application of this method of flow modelling to adequately characterize springs. The fact that the method can be applied to a wide range of spring discharges should be taken as advantage. Thus, identification of sustainable springs can be performed prior to construction.

- ✓ Discharge monitoring on daily basis would better represent the actual field conditions (the variabilities) with more reasonable precision leading to a more realistic output. This can be done easily by installing water meters on each of the spring sources as AAWSA used to do at many sites. However, it is a common experience that water meters frequently fail to function due to many reasons. In such cases the availability of timely maintenance facility for the water meters is a necessity.

- ✓ Further investigations might help to identify additional factors that lead to a negative q_o values other than the geological setting of the spring catchment.

- ✓ Implementation of recharge enhancement techniques in the catchments of the springs would help to increase the volume of infiltrating water ensuring a more sustainable flow.

- ✓ Spring capping structures and main lines should be rehabilitated on time not only to avoid leakage but to increase the precision of discharge measurements during similar studies to obtain good results.

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ANNEXES

ANNEX I: MONTHLY DISCHARGE MONITORING DATA

No.	Spring Name	Date (G.C)	Date (E.C)	Measured Discharge (l/s)	Measured Discharge (l/m)
1	Gojam Ber	Mar-06	Megabit 1998	1.230	73.8
		Apr-06	Miazia 1998	1.090	65.4
		May-06	Ginbot 1998	1.025	61.5
		Jun-06	Sene 1998	1.059	63.54
		Jul-06	Hamle 1998	1.124	67.44
		Aug-06	Nehasse 1998	1.327	79.62
		Sep-06	meskrem 1999	1.370	82.2
		Oct-06	tikimt 1999	1.064	63.84
		Nov-06	Hidar 1999	1.074	64.44
		Dec-06	Tahisas 1999	1.084	65.04
		Jan-07	Tir 1999	0.999	59.94
2	Akako	Mar-06	Megabit 1998	0.570	34.2
		Apr-06	Miazia 1998	0.630	37.8
		May-06	Ginbot 1998	0.766	45.96
		Jun-06	Sene 1998	0.548	32.88
		Jul-06	Hamle 1998	1.059	63.54
		Aug-06	Nehasse 1998	1.193	71.58
		Sep-06	meskrem 1999	1.100	66
		Oct-06	tikimt 1999	0.601	36.06
		Nov-06	Hidar 1999	0.544	32.64
		Dec-06	Tahisas 1999	0.604	36.24
		Jan-07	Tir 1999	0.608	36.48
3	Entoto	Mar-06	Megabit 1998	0.180	10.8
		Apr-06	Miazia 1998	0.270	16.2
		May-06	Ginbot 1998	0.862	51.72
		Jun-06	Sene 1998	1.113	66.78
		Jul-06	Hamle 1998	1.246	74.76
		Aug-06	Nehasse 1998	1.148	68.88
		Sep-06	meskrem 1999	1.210	72.6
		Oct-06	tikimt 1999	2.541	152.46
		Nov-06	Hidar 1999	2.284	137.04
		Dec-06	Tahisas 1999	1.706	102.36
		Jan-07	Tir 1999	0.713	42.78

4	**Fanta**	Mar-06	Megabit 1998	15.120	907.2
		Apr-06	Miazia 1998	15.670	940.2
		May-06	Ginbot 1998	15.500	930
		Jun-06	Sene 1998	15.110	906.6
		Jul-06	Hamle 1998	15.870	952.2
		Aug-06	Nehasse 1998	16.780	1006.8
		Sep-06	meskrem 1999	17.726	1063.56
		Oct-06	tikimt 1999	20.934	1256.04
		Nov-06	Hidar 1999	18.756	1125.36
		Dec-06	Tahisas 1999	16.756	1005.36
		Jan-07	Tir 1999	14.461	867.66
5	**Ras Mekonnen**	Mar-06	Megabit 1998	0.170	10.2
		Apr-06	Miazia 1998	0.210	12.6
		May-06	Ginbot 1998	0.400	24
		Jun-06	Sene 1998	0.462	27.72
		Jul-06	Hamle 1998	0.548	32.88
		Aug-06	Nehasse 1998	0.528	31.68
		Sep-06	meskrem 1999	0.522	31.32
		Oct-06	tikimt 1999	0.564	33.84
		Nov-06	Hidar 1999	0.569	34.14
		Dec-06	Tahisas 1999	0.408	24.48
6	**Yeka**	Mar-06	Megabit 1998	0.150	9
		Apr-06	Miazia 1998	0.347	20.82
		May-06	Ginbot 1998	0.325	19.5
		Jun-06	Sene 1998	0.362	21.72
		Jul-06	Hamle 1998	0.314	18.84
		Aug-06	Nehasse 1998	0.339	20.34
		Sep-06	meskrem 1999	0.410	24.6
		Oct-06	tikimt 1999	0.569	34.14
		Nov-06	Hidar 1999	0.571	34.26
		Dec-06	Tahisas 1999	0.192	11.52

ANNEX II: SEASONAL WATER QUALITY DATA

	Name of Spring	Sampling date (dd/mm/yyyy)	Date of ananlysis (dd/mm/yyyy)	long.	Latit.	Elevation (m)	E.C. µs/cm	Temp. °c	TDS (mg/l)	Turbidity (NTU)	PH	^{14}C(%-mod)	Error	^{13}C(per mill)	Borehole	d18O(Per mill)	d2H (Per mill)	Tritium activity (TU)	Sigma	Total Alkalinity as $CaCo_3$	Na	K	Cl	Phospate as PO4	SiO2	Fluoride as F	Fe	DO	H_2S
Dry Season	Akako	5-Mar-06	21-Mar-06	479600	981100	2140	72		35	Nil	6.7									34			0.5	0.25	7.50	0.03	0.05	6.8	Nil
	Intoto	5-Mar-06	21-Mar-06	473275	1003953	2840	74		36	Nil	6.9							0		28			1.0	0.49	13.80	0.52	0.06	6.8	Nil
	Gojam-Ber	27-May-07		470750	1003800	2840	76		36	Nil	6.9							0.39		44			2.5	0.17	45.60	0.25	0.18		
	Yeka	5-Mar-06	21-Mar-06	478262	1000261	2708	73.5		35	Nil	6.8									156			2.5	0.43	13.70	0.54	Nil	6.8	Nil
	Ras Mekonnen	27-May-07		473262	999303	2465	322		670	Nil										140			71.5	0.29	47.20	0.15	0.13		
	Fanta			479600	981100	2140	536		386	Nil	7.7					_1.65	_1.0	2		218			8.5	0.25	26.20	0.46	0.04		
Wet Season	Akako	11-Aug-06	17-Sep-06	477750	1006250	3140	100		47	Nil	6.89									20			1.5	0.21	9.40	Nil	0.21	6.7	Nil
	Intoto	12-Aug-06	17-Sep-06	473275	1003953	2840	36		16	2.5	7									44			1.0	2.80	8.20	Nil	0.13	6.5	Nil
	Gojam-Ber	10-Aug-06	17-Sep-06	470750	1003800	2840	730		340	2.5	7.32									38			0.5	0.51	31.80	0.12	0.02	6.8	Nil
	Yeka	28-Aug-06	7-Sep-06	478262	1000261	2708	487		233	Nil	8.15									258			5.0	0.10	14.00	1.60	0.01	6.8	Nil
	Ras Mekonnen	12-Aug-06	17-Sep-06	473262	999303	2465	764		368	3	6.94									94			87.5	0.45	27.50	Nil	0.17	6.7	Nil
	Fanta	28-Aug-06	7-Sep-06	479600	981100	2140	199		95	6	8.3									86			2.0	0.18	8.80	0.38	0.07	6.7	Nil
Dr. Berhanu	Gojam-Ber	1999		470750	1003800	2840	63.00	16.50	75.73		5.30										8.50	1.80	0.90	< 0.1	17.00	0.10		3.00	
	Akako	1999		478600	1006350	3150	31.00	15.50	60.99		5.42										4.30	2.30	0.58	<0.1	23.00	<0.1		4.50	
	Akako	1999		478600	1006350	3150	39.00	17.50	89.90		6.14										2.22	1.81	0.62	<0.1	56.00	<1		5.69	
	Intoto (SP- 20)	31-May-2002		473275	1003953	2840	77.30	18.10			6.33	99.70	8.30	_19.05		_3.57	_10.28	0.00	0.80	30.00			10.00	0.05	28.00		0.11	5.80	Nil
	Akako (SP- 14/15)	11-Jun-2002		478600	1006350	3150		15.50			6.25					_3.3	_8.01	14.96	0.67										
	Gojam-Ber (SP - 13)	31-May-2002		470750	1003800	2840										_3.2	_1.43	0.39	0.17										

ANNEX III: SUMMERIZED METEOROLOGICAL DATA

Month	R.F(mm) A.A	R.F(mm) Bole	R.F(mm)Akaki	R.F(mm) Intoto	Relative Humidity (%) (A.A)	Mean MaxTemp (Celcius) (A.A)	Mean Min Temp (Celcius) (A.A)	Sun Shine hr
Jan	17.1	15.6	13.9	15.4	41.2	23.2	8	8.6
Feb	44.8	36.3	36.7	32.7	40	24	9.4	8.1
Mar	71.3	68	60.5	59.2	41.4	24.4	10.8	7.5
Apr	92.3	88.67	91.8	83.4	47.8	23.8	11.3	6.5
May	83.7	78.11	68.3	59.5	43.7	24.4	11.5	6.8
Jun	134.7	120	119.2	128.8	55.5	22.8	10.6	5.1
Jul	272.9	237.8	257.4	297.3	68.8	20.2	10.7	3
Aug	292	238.3	283.8	312	70.2	20.6	10.7	3.2
Sep	188.7	137.6	133.9	148.1	63.2	21	10.5	5.1
Oct	30.7	33.3	23.4	32.1	44.2	22.3	9	8.1
Nov	10.9	5.6	4.4	9.6	40.8	22.5	7.7	9.3
Dec	8.8	5.2	3.6	9.3	40.5	22.6	7.4	9.4