WATER QUALITY AND GROUNDWATER/AKAKI RIVER INTERACTION IN THE SEKELO BASIN (LOWER AKAKI RIVER SUB-BASIN)

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By
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Abstract

The thesis presents the results of geological, hydrogeological and hydrogeochemical studies in the Akaki subbasin (Sekelo). This study was to provide an overview of the water quality and the mixing of the groundwater and the surface water. In the study the geology and the hydrogeology of the area was investigated to provide basic information concerning the different lithologies and the local and sub-regional groundwater flow patterns. The chemistry and the stable isotopic composition of both the groundwater and the river water were considered in order to understand the nature and origin of the waters and to further explain groundwater and river water mixing patterns.

Analysis of the relationship between rainfall and Akaki river shows that the highest flow and level in the river correspondences to the rainy season (June-September). Therefore, influent condition is anticipated during this rainy season. Preliminary water balance estimates using soil moisture budgeting method in the study area suggest 137 mm groundwater recharge annually.

Geological and hydrogeological mapping of the Sekelo basin was conducted in the field and mainly from aerial photograph interpretation. Detailed studies of the geology and the hydrogeology was carried out in the Akaki Well Field D. The rocks of the area are generally volcanic rocks with only minor fluvial sediments. The volcanic rocks are distinguished into lower basalt flows and young basaltic scoria and lava.

Hydrogeological data were collected. These are information from 34 boreholes in the Akaki Well Field D abstracted from records and supplemented by data collected in the field. The types of data collected included lithological information, aquifer parameter data and borehole construction details.

Analysis of these data has shown that on regional scale the groundwater flows from the water divide to the discharge area on the river valleys. The permeabilities of the volcanic rocks in this area are generally high. The important aquifer in the area is the lower basalt in which the aquifers are found in the fractured volcanics and are usually semi-confined. The young basaltic scoria is the main recharge area.

Water samples for hydrochemical and stable isotopic analysis were taken from 9 sites both from the groundwater and river water. Chemical analysis data of 27 boreholes in the Akaki Well Field D was collected from Addis Ababa Water Supply and Sewage Authority (AAWSA) 1996-97. In addition, stable isotopic data of rainfall for Addis Ababa were collected from International Atomic Energy Agency (IAEA) Vienna. Correction was made on these data for altitude difference to get the local meteoric water line.

Analyses and evaluation of these data enabled to obtain information on the nature of the water, in particular the mixing between the groundwater and the river water. The chemical analysis of the groundwater and the river water shows similar Ca-Mg bicarbonate water type. Based on U.S. Environmental Protection Agency's (USEPA) drinking water standard the groundwater proved to have good quality. However the river water which is remarkably influenced by human activities is highly polluted. The evaluation of the chemical composition and stable isotope techniques led to the conclusion that the groundwater can be explained in terms of mixing series between the rain water and the river water.

Chapter One

Introduction

1.1 Objectives

Since many years Legedadi and Gefersa surface water reservoirs in conjunction with groundwater have been supplying the population and industries in Addis Ababa and also in Akaki. The growth in population, improved hygiene, changing habits of consumption, as well as the expansion of industrial production resulted in an enormous rise of the demand of water. First studies concluded that Akaki area embraces ample groundwater resources to provide Akaki itself and Addis Ababa.

To solve the problem of water deficiency, drilling deep wells in Akaki area was chosen as the best solution. In Akaki Well Field D (AAWSA-SEURECA 1991) (in the vicinity of Akaki river) from 1991 to 1997, four deep wells for Akaki town Water Supply and twenty five deep wells for Addis Ababa Water Supply have been drilled and constructed to exploit groundwater by Water Well Drilling Enterprise (WWDE) and China National Complete Plant Import and Export Corporation (COMPLANT) as contractors and AAWSA as a client, respectively.

The water used for industrial purposes and households which come up as wastewater and agricultural runoff are reintegrated into the natural water cycle. Therefore, the increasing of population and the growing of industries, responsible for the elevated water consumption are also accompanied by increased pollution especially of surface water. These contaminants are comprised of organic, inorganic and biological substances, which can cause various health problems. Nitrate which is the main contaminant in agricultural land from fertiliser and animal waste as well from sewage is dangerous to babies because the ability of haemoglobin to transport oxygen will be reduced. In addition, other contaminant like chromium mainly derived from industrial discharge cause problem in liver, kidney and circulatory system. Because of these contaminants in water, which produce adverse effects on the health of humans, it is necessary to check the quality of the groundwaters which are drilled in the Akaki Well Field D for the supply of Akaki and Addis Ababa before supplying the people with the water.

The purpose of this study is to investigate the geology and hydrogeology of a subbasin of Akaki (Sekelo) with particular reference to its hydrochemistry. The study examined in detail the area between Tulu Dimtu in the north and Sekelo in the south, with emphasis on the Akaki Well Field D (Figure 2.1). The ultimate objective of this study is to investigate the interaction between the groundwater and the Akaki river, which is highly contaminated by industrial and urban wastes and agricultural runoff assuming the Sekelo stream is chemically pure and dose not influence the quality of the groundwater by pollution as well to examine, if the water supply from Akaki wells is potable for drinking.

1.2 Previous works

The volcanic stratigraphy of rocks outcropping in the area Addis Ababa-Nazareth have been discussed by Haileselase Girmay and Getaneh Assefa 1989. General hydrogeology of the northern part of the project area is covered in the masters thesis "Hydrogeology of Akaki Area" (Anteneh Girma, 1994). This thesis comprises the area from Bole Arbesa in the north to Tulu Dimtu and Gara Bushu in the south. In addition investigations have been carried out about the feasibility of surface and groundwater for the water supply of Akaki town by AAWSA-TAHAL consultants in 1992. Water well construction reports by AAWSA as a client and WWDE as contractor in 1996. These reports are completed with specific reference to water well drilling, construction, pumping test data, geological and geophysical logs of three large diameter wells and four observation wells. Water quality data of the three large diameter wells in Akaki Well Field D are included. Similar activities have been carried out recently for the 25 water wells drilled in the Akaki Well Field D for the supply of Addis Ababa by AAWSA as a client and COMPLANT as contractor in 1997.

1.3 Approaches followed

The hydrology of the area has been treated shortly in order to know the response of the river in different seasons. Geological mapping of the area has been carried out using the topographic map of SE of Addis Ababa 1:50,000 as a base map. The mapping was conducted in the field and mainly supported by aerial photograph interpretations. In Akaki Well Field D lithologic logs were used to investigate the geology in detail. The hydrogeological characteristics of the different rock units are determined from field and aerial photo interpretations. Geological and electrical logs in Well Field D opened the possibility for comprehensive studies of the hydrogeological characteristics. During the hydrogeological mapping the geological map of the area was utilised as the base map. Moreover, the construction of the deep wells in Well Field D have been assessed. Standard hydrogeological techniques which involve water level data to plot maps (mainly derived from boreholes) and the appraisal of hydraulic properties of the aquifer (normally obtained from pumping tests) have been carried out in this well field.

Hydrochemical and isotopic investigations of groundwater and river water assumes a greater importance in determining mixing patterns, and to identify the possible recharge area. Therefore, sampling for chemical and stable isotopic analysis were undertaken from boreholes (in which pumps are installed) and river water. For the boreholes which are blocked chemical analysis data are collected from AAWSA 1996-97 and stable isotopic composition data for Addis Ababa rain water is collected from IAEA Vienna. The evaluation of chemical analysis data has been carried out to classify the type and origin of the water. The stable isotopic composition in conjunction with chemical composition of the water have been used to determine mixing between the groundwater and the river water.

By converging evidences from hydrology, geology and hydrogeology with that of the hydrochemical and stable isotopic data the relationship between the groundwater and the river water can be studied. This enables the question about the type and origin of the water, areas of recharge and discharge and the interaction between the groundwater and the surface water.

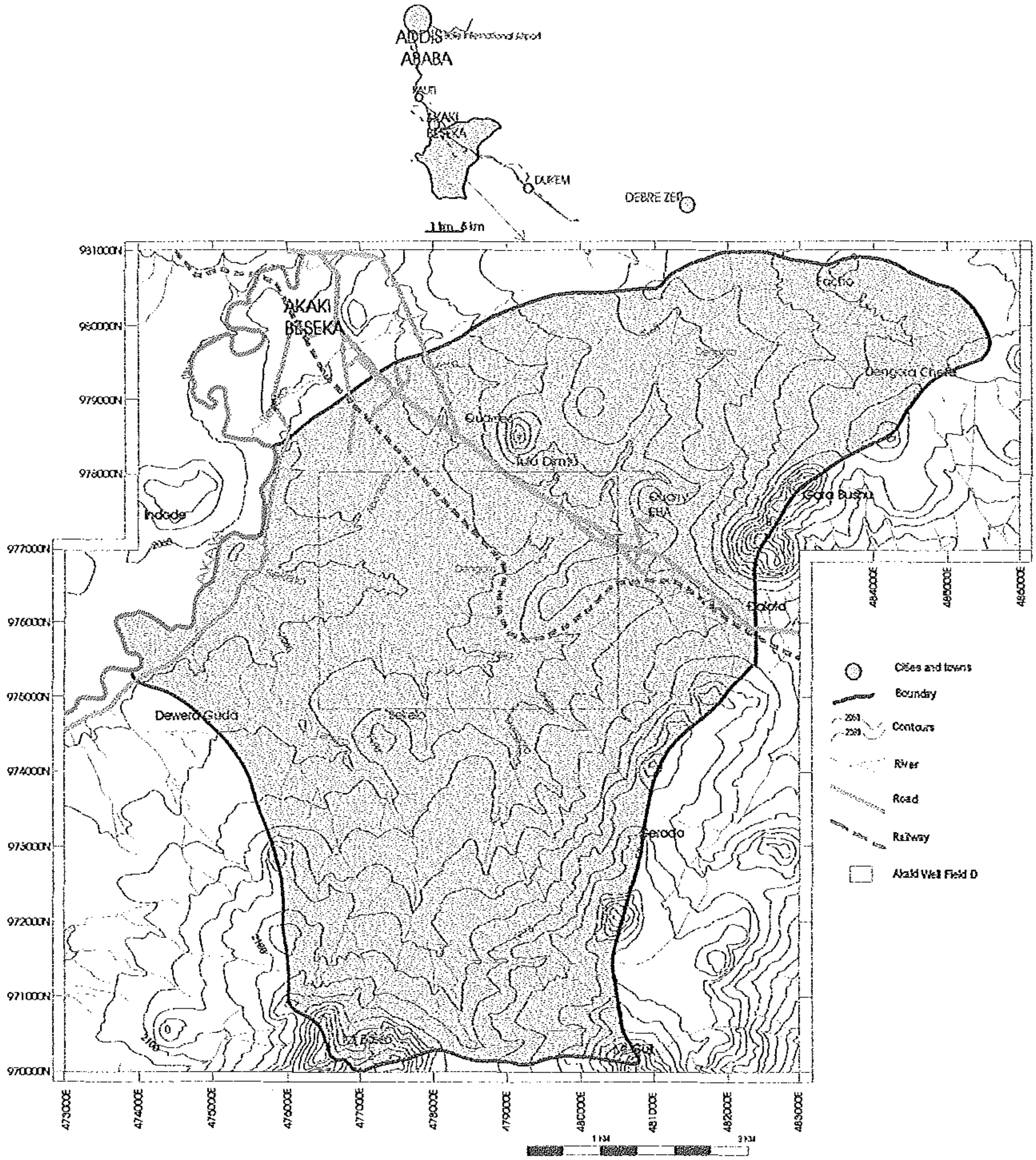


Fig. 2.1: Location map

Chapter Two

Physiography and Hydrology

2.1 Location and topography

The studied area "Akaki subbasin (Sekelo)" is situated in the western escarpment of the Main Ethiopian Rift, 20 km south-east of Addis Ababa, at an average elevation of 2100 m above sea level and is crossed by a railway and the Addis Ababa-Debre Zeit road (Figure 2.1). The area in the east is bounded by a chain of scoria cones from Dengora Chefe in the north to Mt. Guji in the south with a maximum elevation of 2475 m. The southern and south-western boundary scoria cones rise up to 2380 m in Mt. Bilbilo. The Akaki river forms the western boundary where alluvial sediments form even topography. The northern boundary has also relatively flat topography with only minor hills. The central part is characterized by a plain or

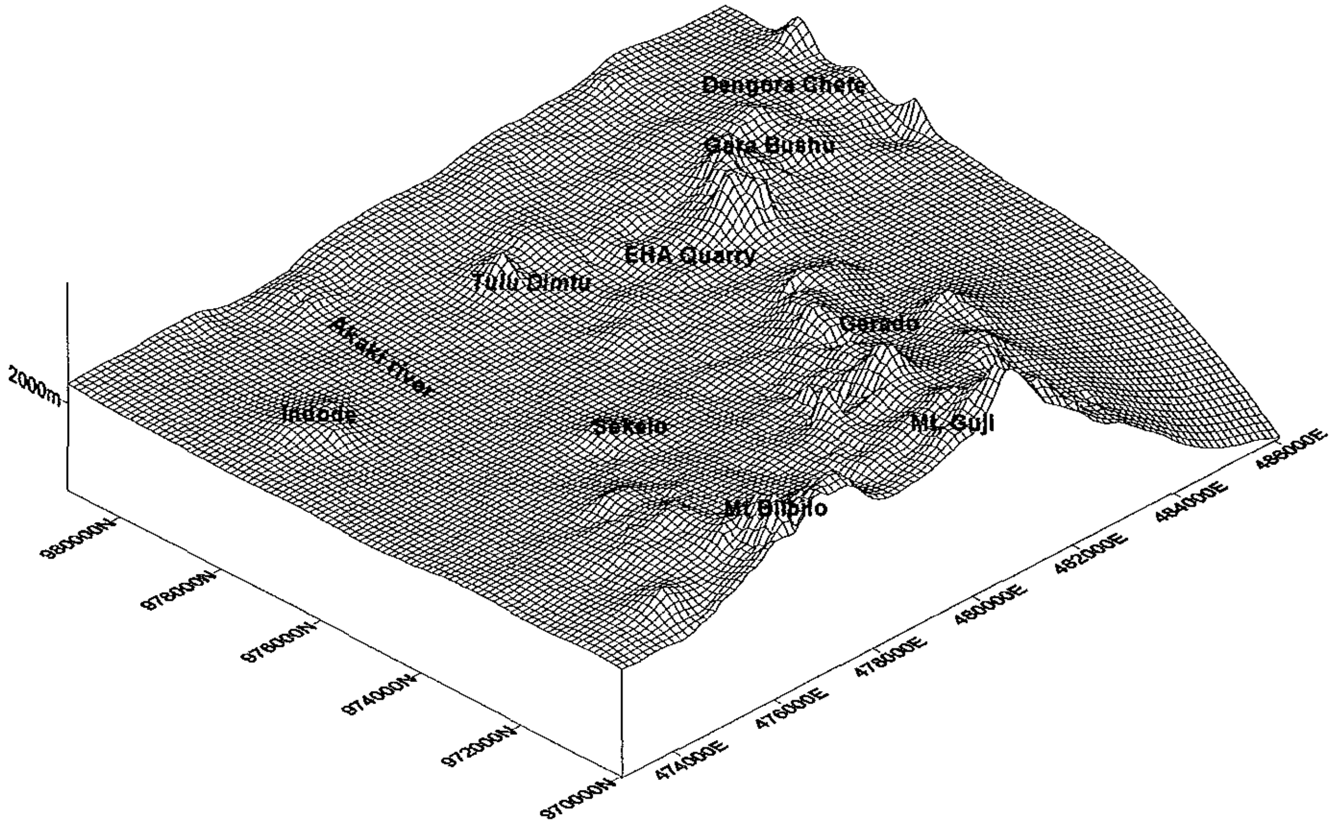


Fig. 2.2: Digital elevation model of the project area

gently undulating terrain with scattered cones of scoria in Sekelo, Ethiopian Highway Authority (EHA) Quarry and Tulu Dimtu. Tributaries of Sekelo stream Aba Bora, Dengora, Keta and Lencho form small gorges. Figure 2.2 is the Digital elevation model (DEM) of the area.

2.2 Land use/ Land cover

Addis Ababa and the town of Akaki Beseka which are highly urbanized are located respectively 20 km and 1 km north-west of the study area. These areas comprise the main industrial zones of the country with various types of industries. The Akaki river passes these regions. Akaki Spare Part Factory is situated in the study area along Addis Ababa-Debre Zeit road. Building stone industry (quarries) like EHA Quarry and Quarries near Tulu Dimtu are present in the study area. In these quarries prospecting is still going on. There are small settlements along the main road in Tulu Dimtu and Dalota and also in the area between Dalota and Gerado around Sekelo and Gara Bushu. The area is intensively cultivated predominantly with teff, wheat and barley. Some shrubs and vegetable gardens are present. Black cotton soil and reddish brown soil are common in the area.

2.3 Climate

The study area is located in the eastern Akaki river catchment. For the discussion of climate and hydrology the records from Addis Ababa Observatory, Addis Ababa Bole and Akaki Beseka stations are utilized.

The study area receives rain fall from Atlantic equatorial wastrelies (June-September) in the months of March, April the moisture comes from gulf of Aden and Indian Ocean. Rainfall is mainly concentrated in to the rainy season of June to September and there is low amount of rainfall in the other months. With in the area the mean annual rain fall ranges from 1066.5 mm at Addis Ababa Bole (1964-1988) to 1207 mm at Akaki Beska (1949-1991) to 1294 mm at Addis Ababa Observatory (1900-1991) with most of the region experiencing an average of 1178 mm (1976-1988) (Anteneh Girma, 1994). The average maximum daily temperature is 22.6°C and minimum 9.8°C (Addis Ababa Observatory data 1949-1991).

The number of sunshine hours ranges on an average from 2.9 in July to 9.4 in December (Addis Ababa Observatory data, 1964-1986). Relative humidity is low throughout the year in the area with mean annual value of 49 %. The mean monthly relative humidity is less than 75 % in July and less than 45 % in February (Addis Ababa Bole data, 1949-1986). The mean monthly wind speed ranges from 0.42 m/s in August to 1.12 m/s in May. The mean annual potential evapotranspiration calculated using Penman method for the years 1982-1986 gave a value of 1276 mm (Anteneh Girma, 1994). The mean annual rainfall for the same year is 1113 mm. This indicate that the potential evapotranspiration exceeds annual rainfall. Monthly average potential evapotranspiration exceed the rainfall by a factor of 1.1 to 12 for every month except in the rainy season from June to September when the monthly precipitation exceeds the potential evapotranspiration. The actual evapotranspiration calculated for the same year using Thornwahite and Mater (1957) method and by making certain correction results in 828 mm annually. Recharge to the groundwater occurs during the wet season.

2.4 Drainage and rainfall-discharge relationship

The Akaki river is a perennial river which has its headwater high in the Entoto ridge and drains the western escarpment of the Main Ethiopian Rift. The eastern catchment of this river includes an area of 902 km^2. The Sekelo basin which is part of the eastern catchment has an area of 60 km^2. The area is characterized by intermittent streams of Aba Bora, Dengora, Keta and Lencho. Denderitic drainage patterns are apparent in the region figure 2.3.

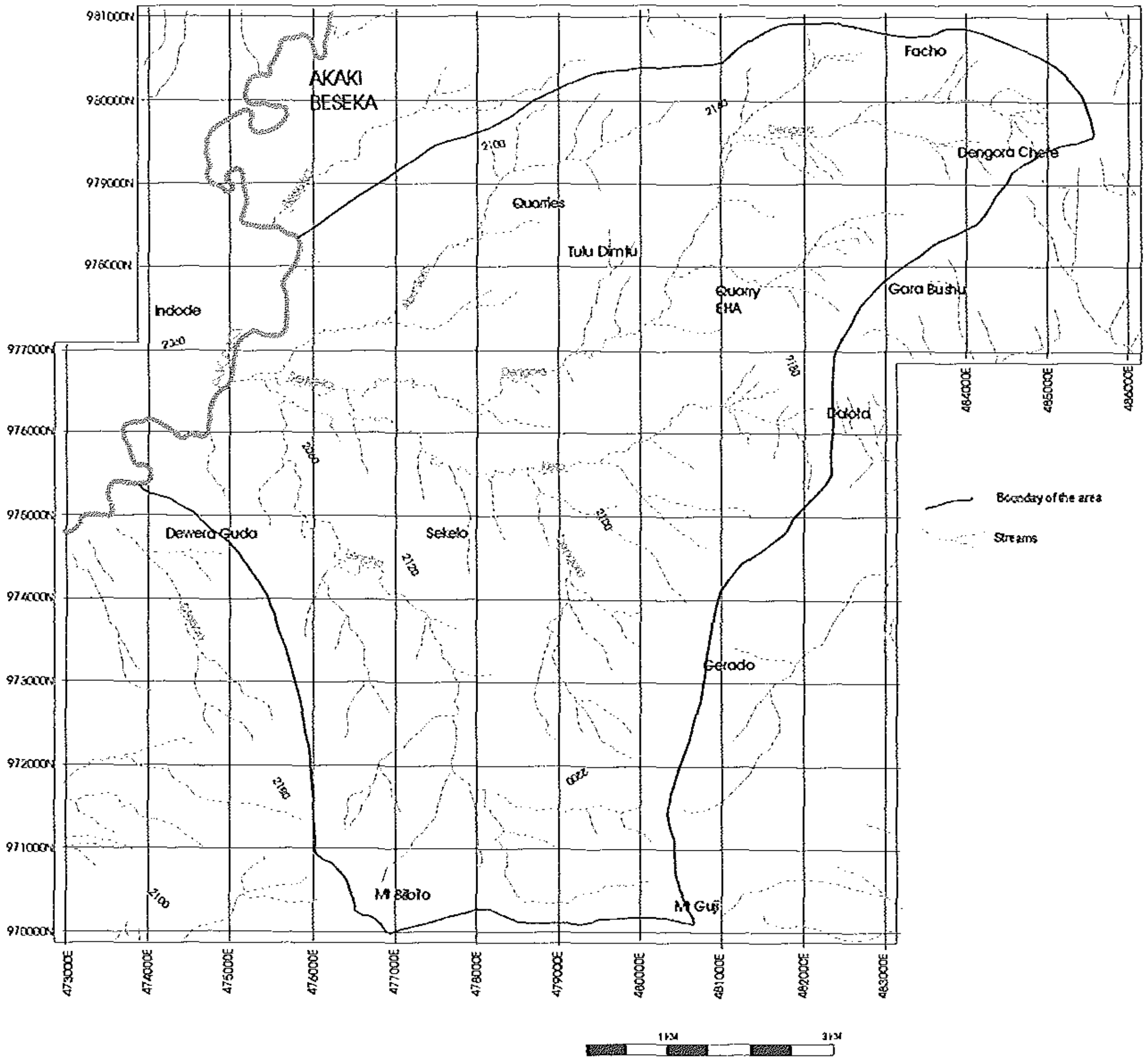


Fig. 2.3: Dendertic drainage pattern of the Sekelo basin

The Akaki river which is perennial is recharged by base flow during the dry season and by precipitation during the rainy season. The mean annual total flow is 6.7 m^3/s (Anteneh Girma, 1994) with higher mean monthly discharge occurring in the months of July, August and September. The increased flow in these months corresponds with high amount and intensity of rainfall. In figure 2.4 it is possible to see how quickly flows respond to the rainfall. There is a time lag before the flow starts to increase after the rain.

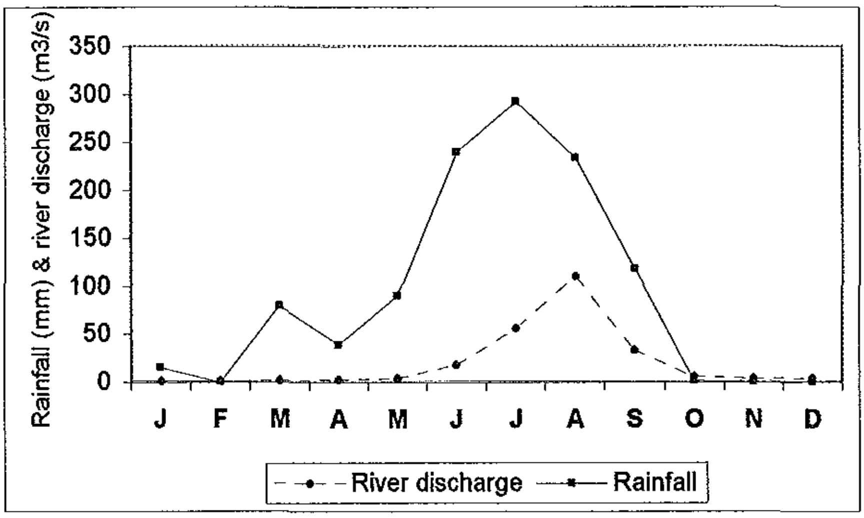


Fig. 2.4: The relationship between river discharge and rainfall (Akaki Beseka station, 1996).

The precise length of this response depends upon catchment size, slope, geology, the amount of rainfall over the recent past few months, the intensity of the rain and the direction in which the storm was traveling across the catchment (Brassington, 1988). In the rainy season the level of the river naturally rises. Daily gauging height of 0.54 m in January to 5.89 m in August are recorded in 1996 at the Akaki Gauging Station (data, Water Resource Development Authority). Groundwater level, on the other hand respond much more slowly. Therefore, during these peak rainy months the river may temporarily become a losing stream (influent), when the hydraulic gradient in the aquifer next to the river is reversed. Water flows from the river into the groundwater. This might also be promoted through increasing pumping

This resulted in an annual value of 137 mm infiltration depth which is uniformly distributed throughout the catchment. Therefore the amount of water recharging the project area in terms of volume can be calculated by multiplying the infiltration depth with the size of the area. According to this method 8.22 million cubic meter water has been estimated to recharge the groundwater in the study area. This is the natural recharge to an undeveloped aquifer. Calculating this value, it was assumed, that the topographic water divide is identical with the subsurface water divide, the amount of water entering into the groundwater is equal to the groundwater leaving the area and the change in soil moisture is assumed to be negligible. This result has limited use. To estimate the recharge exactly more detail studies are necessary

Chapter Three

Geology

3.1 Introduction

Ethiopia was affected by two major tectonic phenomena followed by an important volcanic activity. The first tectonic movement is the epierogenic uplift of Afro-Arabia which occurred on a large scale during Late Mesozoic-Early Tertiary. The upraised and uparched land mass fissuring under tension permitted the extrusion of voluminous basaltic magma estimated 300,000 km^3 (Mohr, 1983) to form the Ethiopian Flood Basalt Province. Geochronological database currently available suggests that widespread volcanism which formed the Trap Basalt of Ethiopia was not initiated until Late Eocene or Early Oligocene.

Superimposed on the long uplifted swell of Afro-Arabia, whose axis approximately runs north-south, part of the Great East African Rift System started to develop in the Miocene. Rifting has commenced previously in Red Sea and Gulf of Aden which are at present partly underlain by oceanic crust. The younger and continental Main Ethiopian Rift (MER) joins the Red Sea-Gulf of Aden structure at the complex ('proto-oceanic') Afar Depression. The MER which is an important segment of the continental East African Rift trends in NNE-SSW and runs from Lake Chamo to about the latitude of Addis Ababa where the rift starts to widen northwards into the Afar Depression.

According to Kazmin et al., (1980), initial sagging of the MER started about 14 to 15 My and was followed by major episodes of rifting at 10, 5, 4 and 1.8 to 1.6 My. Each stage of rifting and downfaulting was accompanied by a bimodal (silicic-mafic) volcanism in the rift and formation of basaltic and trachytic shield volcanoes on the rift shoulders and margins.

3.2 Regional geology of Addis Ababa-Debre Zeit region

The Addis Ababa-Debre Zeit Region which is part of the western margin of the Main Ethiopian Rift is covered by Miocene-Pleistocene volcanic products and affected by NNE-SSW trending normal fault. Lithostraigraphic divisions and the correlation of the Miocene-Pleistocene volcanic succession in the Addis Ababa-Debre Zeit area is shown below (Haileselase Girmay & Getaneh Assefa, 1989).

Stratigraphic unit	**Representative lithologies**	**Age**	**Correlative to**
Wonji Group	Aphanatic basalt		
	Weakly welded tuff	0.51 My	Wonji series
	Porphyritic plagioclase basalt	0.61 My	Winji group
	Strongly welded tuff	1.7 My	
Bofa Basalts	Olivine basalt	2.8 My 2.9My	Bishoftu Basalts Bofa Basalts
Nazareth Group	Upper welded tuff	3.2 My	Balchi Rhyolites Pliocene Silicics
	Aphanitic basalt	3.5 & 3.9 My 3.6 My	Nazareth Series Nazareth Group
	Lower welded tuff	5.1 & 5.4 My	
Addis Ababa Basalts	Plagioclase basalt, Olivine basalt	6.4 My 6.9, 7.1 & 7.3 My	

Table 3.1: Lithostratigraphic divisions and correlation of the Miocene-Pleistocene volcanic succesion in the Addis Ababa Debre Zeit area.

The classification of the Bofa Basalts and Bishoftu Basalts is made according to Mengesha Tefera et al., 1996.

3.2.1 Addis Ababa Basalts

The Addis Ababa Basalts outcrop within the city of Addis Ababa from the foothills of Entoto to Filwoha area. The basalt flows have porphyritic texture with labradorite-bytownite, olivine and augite as phenocrysts and andesite, labradorite, olivine, opaque oxides and clino-pyroxene characterise the groundmass. As the Addis Ababa Basalts are restricted to the western escarpment of the rift in Addis Ababa their emplacement might have been preceded by faulting. These basalts have been dated 7-6.4 My and have no compositional or time equivalent in the western and eastern escarpment of the rift. The absence of volcanic rocks equivalent to Fursa and Anchar basalts dated 14-10 My, indicates that the formation of the rift margin in Addis Ababa area is younger than the opposite margin in the east and the western escarpment north of Addis Ababa. The Addis Ababa Basalt is affected by the NE-SW trending Filwiha Fault (6.4-5 My), which is down thrown to the south (Haileselase Girmay & Getaneh Assefa, 1989).

3.2.2 Nazareth Group Volcanics

The Nazareth Group Volcanics outcrop south of Filwiha Fault and extend south to Nazareth town. The name is used to a thick succession of ignimbrites with fiamme, pumice, ash and rhyolite flows and domes with intercalations of basalt flows. These Volcanics occur in the MER, the rift margins and adjacent plateaus (Kazmin & Berhe, 1978). The Nazareth Group Volcanics in the Addis Ababa Nazareth region are possibly products from central volcanoes and can be placed in the age range of 6-3 My (Haileselase Girmay & Getaneh Assefa, 1989).

3.2.3 Bofa Basalts

The name Bofa Baslts was used by Kazmin & Berhe (1978) for a series of olivine basalt flows overlying the Nazareth Group and later this name was used by the Ethiopian Institute of Geological Surveys (E.I.G.S.) (Kazmin et al., 1980b) to all Pliocene rift floor basalts. The Bofa Basalts are well developed in the northern and central part of the MER and out crop in the Akaki-Debre Zeit area. These basalts are flood flows and commonly aphyric, vesicular and fresh with several flows separated by scoracious horizons. Deep drilling for geothermal exploration in Aluto-Langano within the MER has shown that the Bofa Basalts posses thickness of more than 500 m (Mengesha Tefera et al., 1996). This indicates the occurrence of an important flood basalt volcanism in the MER during Pliocene. Quaternary pyroclastic products and continental sediment overlie the Bofa Basalts. The Bofa Basalts were extruded after complete development of the rift.

3.2.4 Bishoftu Basalts

The name Bishoftu Basalts was given by Zanettin et al., 1974 and Kazmin et al., 1980 to Plio-Pleistocene basalt flows with numerous well preserved scoria cones on the margin of the MER south of Addis Ababa. The lower age limit lies around 2 to 2.8 My. These basaltic lava flows are alkaline in composition and probably controlled by cross-rift transverse structures in the MER. This particular location makes them different from the correlative basalt of the Bofa Basalts (Mengesha Tefera et al., 1996).

3.3 Geology of the study area

3.3.1 Introduction

The study area lies between Addis Ababa-Debre Zeit region at the western margin of the MER. The description of the geological units of the study area is based mainly on data obtained from shallow drill logs performed by AAWSA, WWDE and COMPLANT (1991-97) However, additional field investigations and aerial photo interpretation have been carried out to draw the geologic map (figure 3.6). The rocks that cover this area are almost all volcanic in origin with subordinate fluvial sediments. The volcanic rocks are distinguished into two: lower basalt flows and younger basaltic scoria and lava.

From field investigations and description of shallow drill logs (appendix 1) it is observed that the lower basalt flows constitute the oldest outcropping rock unit and the alluvial sediments along the Akaki river form the youngest unit.

Lower basalt flows are exposed in the western part of the study area. From observation of the geologic log of the area it can be distinguished that several flows of basalts are separated by pyroclastic deposits. The logs show intercalations of massive basalt, scoracious basalt and pyroclastic rocks such as scoria and tuff. This intercalated unit dominated by basalt flows belongs to the Bofa Basalt unit described by previous investigators (Mengesha Tefera et al., 1996). This indicates that the Bofa Basalts are the results of several volcanic eruptions.

The eastern portion of the study area exposes younger basaltic rocks dominated by scoria cones and associated flows. These are different from those described in the western part of the area. These rocks are known as Bishoftu Basalts in the literature (Mengesha Tefera et al., 1996). Scattered cones of basaltic scoria are also exposed in the west and south-west of the area. The scoria cones are aligned along NE-SW direction, parallel to the trend of rift faults. The typical rock exposures consist of an accumulation of volcanic bombs and lapilli that have built scoria cones with scoracious basalt flows out poured from the vent and capping the cones. Volcanic breccia and surge deposits are found further away from the vent. This Younger basaltic scoria cones and lava flows are probably formed from magma with a relatively higher viscosity and higher dissolved gas content than effusive magmas (Hall, 1992).

The basaltic lava flows and associated pyroclastics are in places covered by Quaternary fluvial sediments. The alluvial sediments along the Akaki river and Sekelo stream are the youngest rock unit, still currently being formed.

3.3.2 Description of the rock units

3.3.2.1 Lower basalt flows

The lower basalts in the study area are mostly covered by soil and exposed in only few localities. Basaltic lava flows were observed between Tulu Dimtu and EHA Quarry. Tuff layers intercaleted with basalt flows are exposed near Sekelo stream.

Bore hole logs drilled upto 170 m of depth show the intercalation of massive basalt, scoracious basalt, basaltic scoria, tuff and weathering products of these rocks. This is typical of Bofa Basalts in which several flows of basalts are separated by scoracious horizons. The maximum thickness of the massive basalt is around 60 m near Tulu Dimtu (bh05a appendix 1) and minumum thickness is around 3 m. The maximum thickness of scoracious basalt reaches up to 25 m. The scoracious horizons which separate the different baslaltic flows comprise a maximum thickness of 50 m. The correlation of the lithologic variations in the various drill holes proved to be difficult. As the boreholes show an abrupt change of lithology from one to the other. The possible reason for this can be that the flow of basalt is local or there might be error in the data set of the lithologic log. Most probably there is error in the data set as it can be seen in bh04 and bh26 (appendix 1) within 800 m distance there is an abrupt change of thickness of massive basalt from 25 m to 5 m. Since the boreholes are concentrated in small area, they show the same formation (lower basalt flows) except the boreholes in the eastern part of the area (bh06, bh07, bh08) (appendix 1) in which the lower basalt flows are covered by younger volcanic breccia. From this it can be concluded that there is younging of the rock from west to east. For the details of the lithologic log see appendix 1.

Basalt flow of the lower basalt unit is best exposed between Tulu Dimtu and EHA Quarry along Dengora stream. The outcropping section has a thickness of around 5 m. It is a highily fractured and grey coloured rock. It is composed of labradorite, olivine and augite as phenocryst. Labradorite, andesine, clinopyroxine and olivine form the groundmass. Calcite exists as secondary mineral in veins and may act as a substitute of plagioclase (Haileselase Girmay. & Getaneh Assefa, 1989).

A layer of unwelded tuff is exposed near the Sekelo stream along a valley and has exposed thickness of around 2 m. This is the pyroclastic rock intercalating with the basalt and scoracious basalt of the lower basalt flows. It is highly weathered and has very fine texture. This is shown in figure 3.1.

Fig. 3.1: Highly weathered tuff underlying a soil cover

3.3.2.2 Younger basaltic scoria and lava

Younger basaltic scoria and lava are aligned spatter cones in NE-SW direction in the east of the area from Facho to Mt. Gugi. Scattered cones exist in the south-west Mt. Bilbilo, in the west Sekelo and the area between Mt. Bilbilo and Dewera Guda as well in the north-west in Tulu Dimtu. These younger basalts consist of volcanic breccia, surge deposit, basaltic scoria and scoracious basalt.

Volcanic breccia is underlain by lower basalts. This rock outcrops along Addis Ababa-Debre Zeit road south of EHA Quarry (figure 3.6). The thickness of the volcanic breccia reaches up to 20 m. It contains aggregate of blocks of variable sizes. The finer material is light in colour and the blocks are commonly black. The size of these blocks reaches up to 1 m in diameter.

Surge deposits are exposed in the north-east along Dengora stream and in the west along Lencho stream (figure 3.6). The surge deposit has grain size is in the range of sand and is poorly sorted. Grey colour is prevailing in this rock.

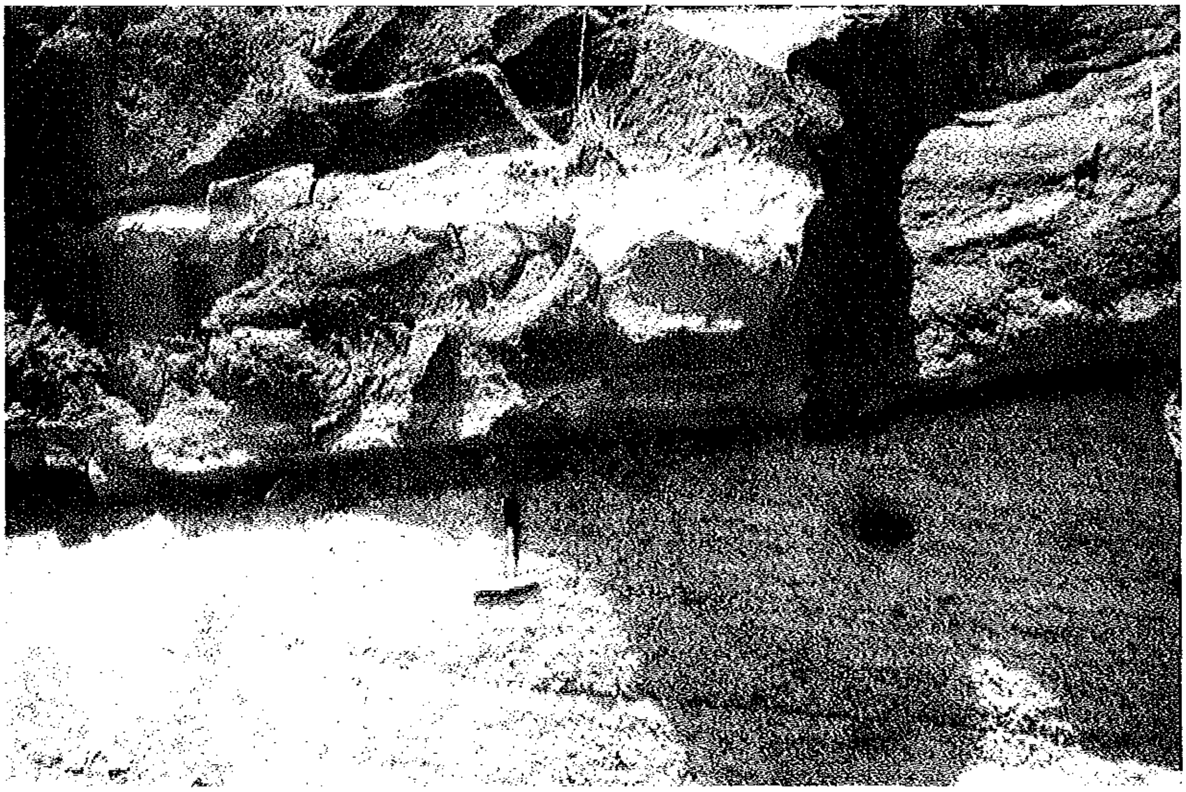


Fig. 3.2: Surge deposit overlying scoria along Lencho stream

Along Lencho stream, the thickness of the surge deposit is 2 m and is overlying earlier formed scoria. At the contact of the surge deposit and the scoria the boulders are rounded (figure 3.2). The surge deposit along Dengora stream has exposed thickness of 5 m. Cross bedding up to 30 cm thickness and lamination appear (figure 3.3).

Fig. 3.3: Cross bedded surge deposit along Dengora stream

Basaltic scoria cones cover large part of the study area. They outcrop in Facho, Dengora Chefe, Gara Bushu, EHA Quarry and Tulu Dimtu localities. Aligned cones emerge south of Dalota in Gerado, Mt. Guji, in the south-west Mt. Bilbilo and in the west scattered cones of scoria in Sekelo and north of Mt. Bilbilo. Height of the scoria cones range from 10 m north of Mt. Bilbilo to 200 m in Mt. Guji. The scoria observed in these areas are vesicular and are generally in the size range of lapilli or larger. They are mafic in composition and are red in colour because of iron oxide in scoria.

In the Tulu Dimtu Quarry the height of the scoria cone is 50 m. It is thickly bedded and the thickness of the bed reaches up to 1 m. The grain size ranges from 2-5 cm, along the bedding plane the grains are finer. It has red colour because of iron oxide (hematite). It is composed of feldspar and mafic minerals like olivine figure 3.4.

In EHA Quarry the height of the scoria cone reaches up to 40 m. It has inclined bedding dipping NW-SE direction and the thickness of the beds reaches up to 1 m. The grain size ranges from lapilli size to bombs up to 20 cm in diameter. It is highly weathered and the colour is yellow, this yellowish colour is because of the weathering of iron oxide (figure 3.5).

Fig. 3.4: Red scoria cone exposed in Tulu Dimtu

Scoaracious basalts are found at the top of scoria cones. This rock was observed in Tulu Dimtu, Gara Bushu, Gerado, Mt. Guji, and Mt. Bilbilo. The thickness of scoracious basalt ranges from 10 m north of Mt. Bilbilo to 90 m in Mt. Bilbilo. The scorascious basalt in Tulu

Dimtu area has a thickness of 40 m. Big bombs of rocks show porphritic texture. Prevailing colour is grey to black. It is composed of olivine and pyroxine.

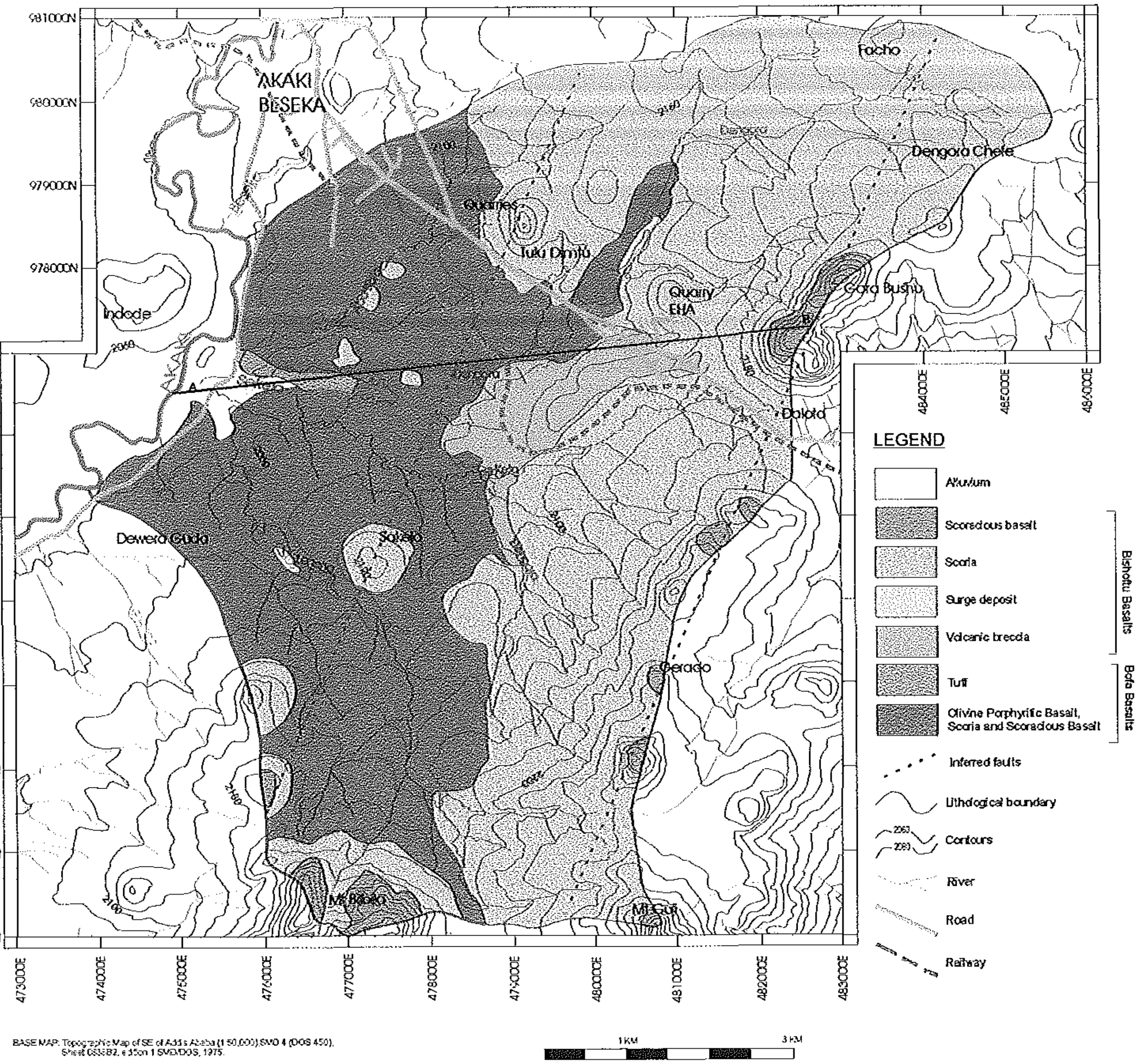
Fig. 3.5: Highly weathered scoria cone with inclined bedding.

3.3.2.3 Alluvial sediment

Alluvial sediment is observed along the Akaki river and Sekelo stream. The sediment covers a small area in the north along Akaki river and covers wider area to the south. The alluvial sediments are localised in flat lying area. The Akaki river is a meandering river and the alluvial sediment has grain size ranging from gravel to sand.

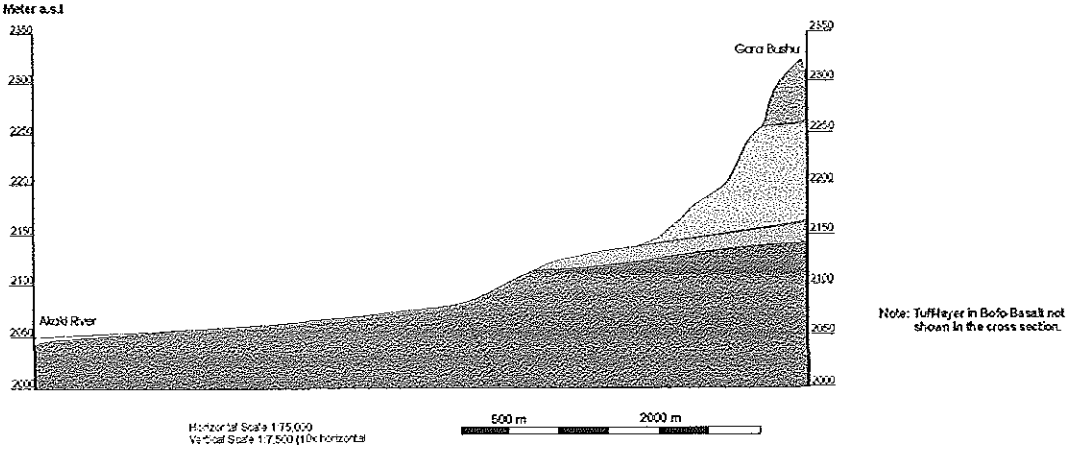
GEOLOGICAL MAP OF AKAKI SUBBASIN (SEKELO)

Scale: 1:75,000



BASE MAP: Topographic Map of SE of Addis Abeba (1:50,000) SMO 4 (DOS 450), Sheet 0838B2, edition 1 SMO/DOS, 1975.

GEOLOGICAL CROSS SECTION A-B



Note: Tuff-layer in Bofa Basalt not shown in the cross section.

Horizontal Scale 1:75,000
Vertical Scale 1:7,500 (10x horizontal

Fig. 3.6: Geological map and Geological cross section of Akaki subbasin (Sekelo).

Chapter Four

Hydrogeology

4.1 Introduction

4.1.1 Hydrogeological Setting

According to Tesfaye Chernet (1993) the aquifers of Ethiopia are classified based on aquifer type and productivity. Concerning aquifer type the country is classified into five aquifer areas:

- 1-Extensive aquifer with intergranular permeability (unconsolidated sediments: alluvium, eluvium, colluvium, lacustrine sediments, poorly cemented sandstone).
- 2-Extensive aquifer with fracture and/or karstic permeability (consolidated sediments and metamorphosed carbonates: limestone, sandstone, evaporite, marble associated with shale, marl).
- 3-Extensive aquifer with fracture permeability (volcanic rocks: basalt, rhyolite, trachyte, ignimbrte).
- 4-Localaised aquifer with fracture and intergranular permeability (noncarbonate metamorphic rocks, granitic intrusives, dolorites)
- 5-Main geothermal areas, common occurrence of thermal groundwater in fractured volcanic rocks and subordinate unconsolidated sediments

Based on aquifer productivity, the different aquifers are classified into three:

- 1-High productivity aquifer permeability value ranging 0.62-124 m/day.
- 2-Moderate productivity aquifer permeability value ranging 0.14-62 m/day.
- 3-Low productivity aquifer permeability value ranging 0.004-0.14 m/day.

Tectonic movements have important effects on the hydrogeology of Ethiopia. The Ethio-Arabian swell and the formation of the rift valley in Late Mesozoic and Early Tertiary times mainly control the nature and orientation of the present basin. The other wide spread factor which affect the hydrogeology of Ethiopia is the tectonic movement which produced secondary porosity and permeability by fracturing and jointing. This is more pronounced in the rift valley and the escarpment. Faulting and fracturing have increased the permeability of volcanic rocks in the rift valley especially of the basalts and some ignimbrites. There was fissural eruption through faults in the rift valley which contributed to permeable lava in this area (Tesfaye Chernet, 1993).

4.1.2 Scope of the study of the hydrogeology of the area

Knowledge of the hydrogeology of the project area varies considerably and depends primarily on the distribution of water supply boreholes. In the Akaki Well Field D, for example, over 30 boreholes have been drilled up to a depth of 170 m since 1990, whereas no deep boreholes have been drilled outside this area. Hydrogeological field investigations have been carried during the project. These include observation of the degree of fracturing of the rock, the thickness of the formations, the grain size and sorting, clay proportions and the extent of weathering. Evaluation of the pumping test data in the Akaki Well Field D has been done to determine the aquifer properties.

The hydrogeological assessment was performed after an international standard legend for hydrogeological mapping (Struckmeier et al., 1995). From hydrogeological observations and from the result of the evaluation of the pumping test data, the study area can be divided in to three:

1. An extensive aquifer with fracture permeability is the main aquifer covering large parts of the western area.
2. scoria cones with fracture and/or intergranular permeability which is a good recharge area for the extensive lower basalt flows.
3. A localised aquifer with intergranular permeability which is the alluvium exposed along the Akaki river and Sekelo stream.

During the project, borehole data in the Akaki Well Field D have been used: first, to investigate the aquifer characteristics of especially the lower basalts, secondly, to discuss the well construction, thirdly, to construct static water level map of the Akaki Well Field D in attempting to determine the groundwater flow direction and finally an attempt has been made to determine aquifer properties

4.2 Aquifer characteristics of the different rock units

4.2.1 Lower basalt flows

The lower basalt group covers a large part in the west of the study area. Boreholes drilled in Akaki Well Field D up to a depth of 170 m are composed of lower basalt flows. An attempt has been made to evaluate the geological log, resistivity log and self potential log of the borholes in Akaki Well Field D. Since resistivity and self potential logging are only possible below the static water level, the evaluation of the upper part of the borehole depends solely on the geologic log.

Variation in resistivity are caused primarily by differences in the character of the subsurface rock and the presence and quality of water. Dry formations have poor electrical conductance and show very high resistivity. Increasing water saturation of the pores or cavities in the formation reduces its resistivity; the reduction in resistivity is partially controlled by the porosity. This occurs because water (in its natural condition) is an electrical conductor, so its presence in the interconnected cavities reduces the overall formation resistivity. There are, however, general difference in the resistivity of various saturated formations. silt, clay and shale, for example, have very low resistivity; sand and gravel with fresh water have moderate to high resistivities. In addition to aquifer material, water quality also affects resistivity. Formations filled with highly mineralised water show relatively low resistivity. In contrast, those saturated with fresh water have relatively higher resistivity (Fletcher & Driscoll, 1995).

Self potential logging is used for acquisition of information concerning the salinity of water in porous (permeable) rock. For quantitative interpretation of self potential logs a shale/sand alternating bedding is a precondition. In water-filled drill holes in rock with fracture permeability usually no interpretable SP curve is attained (Repsold, 1989).

As it can be proved from the geologic logs, the formation is basaltic. In addition to this, results of water quality analysis show fresh water. Therefore, the shape of the resistivity log curves depend mainly on the degree of fracturing and the presence or absence of water. The water in the fissures contains ions (e.g. Na^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}) which reduce the resistivity of the rock. Because of the limiting factor to use the spontaneous potential (SP) log in this formation, resistivity log curves are mainly used in conjunction with the geologic log to evaluate the boreholes. However, in some boreholes SP curves show good correlation with resistivity curves.

The geologic log distinguishes the following rocks: massive basalt, scoracious basalt, scoria, tuff, clay, weathered and fractured basalt, scoracious basalt, scoria and tuff. In addition, baking effects are marked in the logs. It indicates that this formation is formed by several flows of basaltic lava separated by scoracious horizons and affected by tectonic movements. The tectonic stress which is noticeable in the rift and rift escarpment is an important factor for the creation of openings enhancing secondary permeability and porosity. Chemical and physical weathering are further responsible for developing fractures/fissures and clay minerals. This weathering, especially during the interval between the flows, may also increase the aquifer quality. On the other hand, the amount of clay derived from the weathering of basaltic rocks can reduce the permeability and the effective porosity. The baking effects which indicate the contact zone between lava streams having been heated up rapidly are rather permeable due to the abundance of fissures. The high permeability of the contact zone is proved by low value of apparent resistivity ranging from 50 to 100 Ωm.

scoria and in some boreholes unwelded tuff layers interbedded in between the basalt flows have intergranular and fracture permeability and are good aquifers. Scoracious basalts have high porosities but low permeability as the pores are often not connected with each other. In contrary to this fact, the scoracious basalts in the Akaki Well Field D often show both high porosity and permeability. This indicates that these rocks are affected by tectonic activity resulting in fracture permeability. The appearance of the basalt in this well field shows all stages from massive to highly fractured and weathered. The fractured and weathered basalts have high porosity and fracture permeability. Massive basalt and slightly fractured basalt act as aquiclude and aquitard, respectively. Apparent resistivity value of these basalts vary from 300 to 2000 Ωm. The maximum thickness of these two units reaches up to 60 m in bh05a (appendix 1), which proved to be a dry borehole. The weathering product of basalt, clay, has a high total porosity but very low effective porosity and therefore also low hydraulic conductivity. Reduction of the secondary permeability originates from deposition of clay in the fractures, limiting water movement. Clay layers are pronounced in few boreholes (e.g.

bh02, bh03b bh17). Therefore, clay layers are not assumed to be laterally extensive. They may lead to perched aquifer situations where they are overlain by more permeable rocks. In bh03b the maximum thickness of this aquiclude is around 15 m (appendix 1).The apparent resistivity value in this case varies from 5 to 100 Ωm. Fractured basalt, scoracious basalt and scoria which are aquifers vary in thickness from more than 100 m to only 2 m. These fractured basaltic rocks have an average range of apparent resistivity value 50 to 300 Ωm.

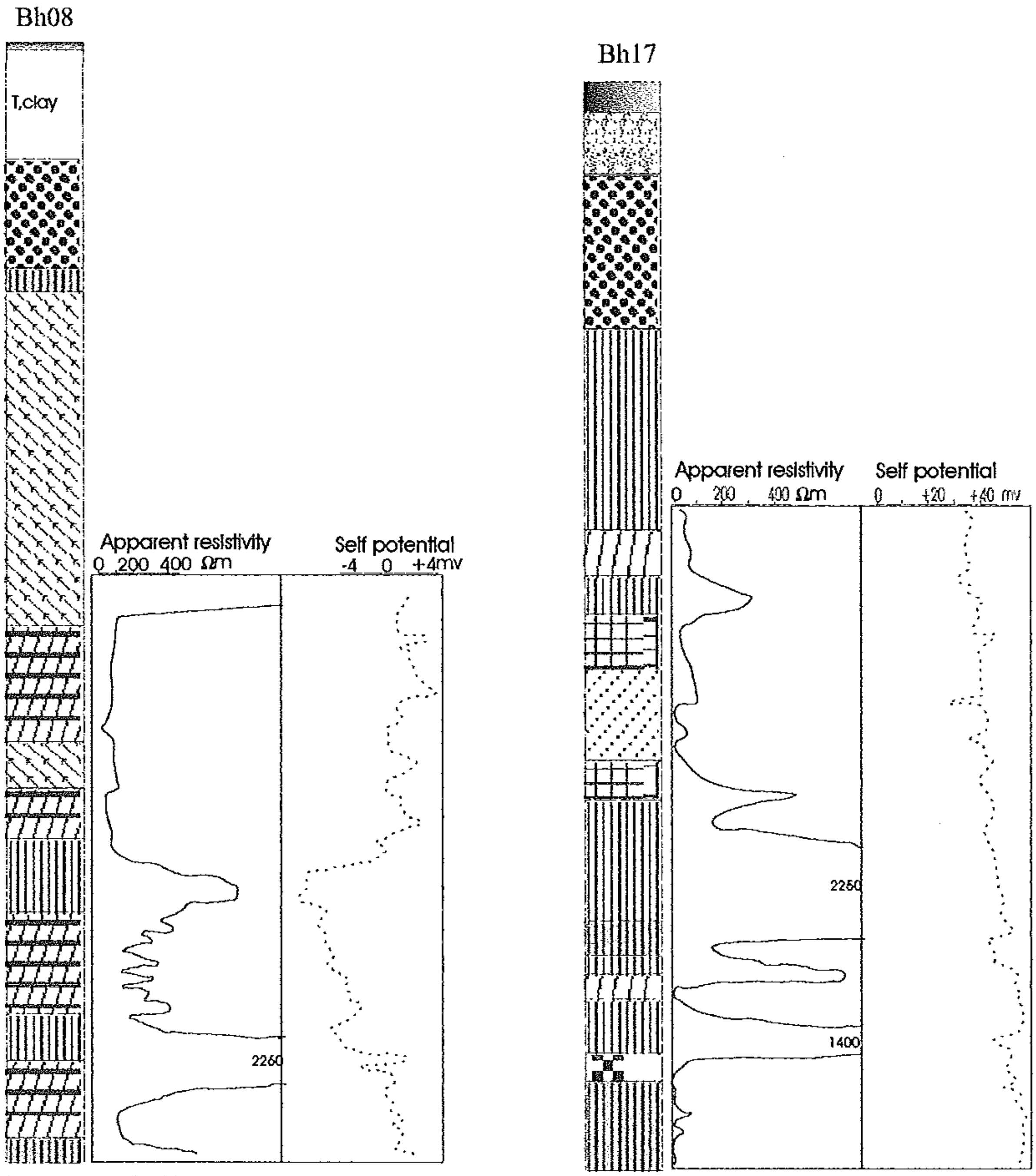


Fig. 4.1: Electrical logs of boreholes bh08 and bh17. Total depth of bh08 is144 m and bh17 is 141 m. The legend for geologic logs is shown in appendix 1 (modified AAWSA).

Evaluation of pumping test data revealed that the transmissivity of the aquifer lie in the range of 389 to 21600 m^2/day. According to Tesfaye Chernet (1993), these aquifers can be considered as highly productive. All the boreholes drilled in Akaki Well Field D show more or less similar intercalations of rocks and transmisivity. As discussed in the previous chapter this formation is well developed in this area up to Debre Zeit. Based on the above explanations, this unit can be classified as an extensive aquifer with fracture permeability and highly productive. Borehole logs of lithology, apparent resistivity and self potential are shown in figure 4.1.

4.2.2 Younger basaltic scoria and lava

Younger basaltic scoria and lava group is exposed from north-east to the south-east and in only few areas in the south-west. This group consists of volcanic breccia, surge deposit, basaltic scoria and scoracious basalt.

4.2.2.1 Volcanic breccia

Volcanic breccia is localised in the east of the area south of EHA quarry. It is overlying the extensive aquifer of the lower basalts. It covers an area of approximately 5 km^2 and the thickness reaches up to 20 m. The grain size is ranging from ash to blocks. Fracturing and jointing is perceptible in the outcrop. The unit has good porosity and permeability. Because of its limited thickness and areal extent, it is unimportant for exploring groundwater. However, it permits infiltration of water for recharging the underlying extensive aquifer of the lower basalts.

4.2.2.2 Surge deposit

Surge deposit outcrops along Dengora stream near EHA Quarry and along Lencho stream are very limited. The thickness of this rock reaches 2 m in the Lencho stream and the exposed part along Dengora stream is around 5 m. It is poorly sorted. The surge deposit along Dengora stream is highly consolidated whereas along Lencho stream is weakly consolidated. Therefore, the rock along Lencho stream has higher porosity and permeability compared to Dengora stream surge deposit. In both areas the rocks are not tectonically affected, so they have intergranular permeability. While these rocks are restricted in small area and have only few meters of thickness, they are hydrogeologically insignificant. Nevertheless, they may allow direct infiltration recharging the underlying lower basalt flows.

4.2.2.3 Basaltic scoria cones

Basaltic scoria cones are exposed in the area from Facho in the north-east to Mt. Guji in the south-east and Tulu Dimtu in the north-west. Scattered scoria cones are observed in the south-west Mt. Bilbilo and in the west Sekelo and the area between Dewera Guda and Mt. Bilbilo. In contrast to lower basalts group, the scoria cones are controlled by the transversal structures in the MER. They are localised along faults and fissures. The exposed height of the scoria cones vary from 10 m in the west to 200 m in Mt. Guji. The size of the pyroclastic material ranges from lapilli to boulder. Scoria cones consist from fresh to highly weathered and fractured rock. For example, the scoria cone in Tulu Dimtu quarry is fresh with marked bedding structures. The grain size in this scoria ranges from 2-5 cm. The scoria cone in this area is characterised by intergranular permeability. However, the scoria cone in EHA Quarry is highly fractured and weathered. Grain size varying from lapilli to boulders. This scoria cone shows fracture and intergranular permeability. In general the scoria cones have either intergranular or intergranular and fracture porosity and permeability. Nevertheless, these cones are localised in small area and they cannot yield water to wells. Therefore, they cannot be categorised as aquifer. Yet, these scoria cones are high recharge area for the lower basalt flows in this region.

4.2.2.4 Scoracious basalt

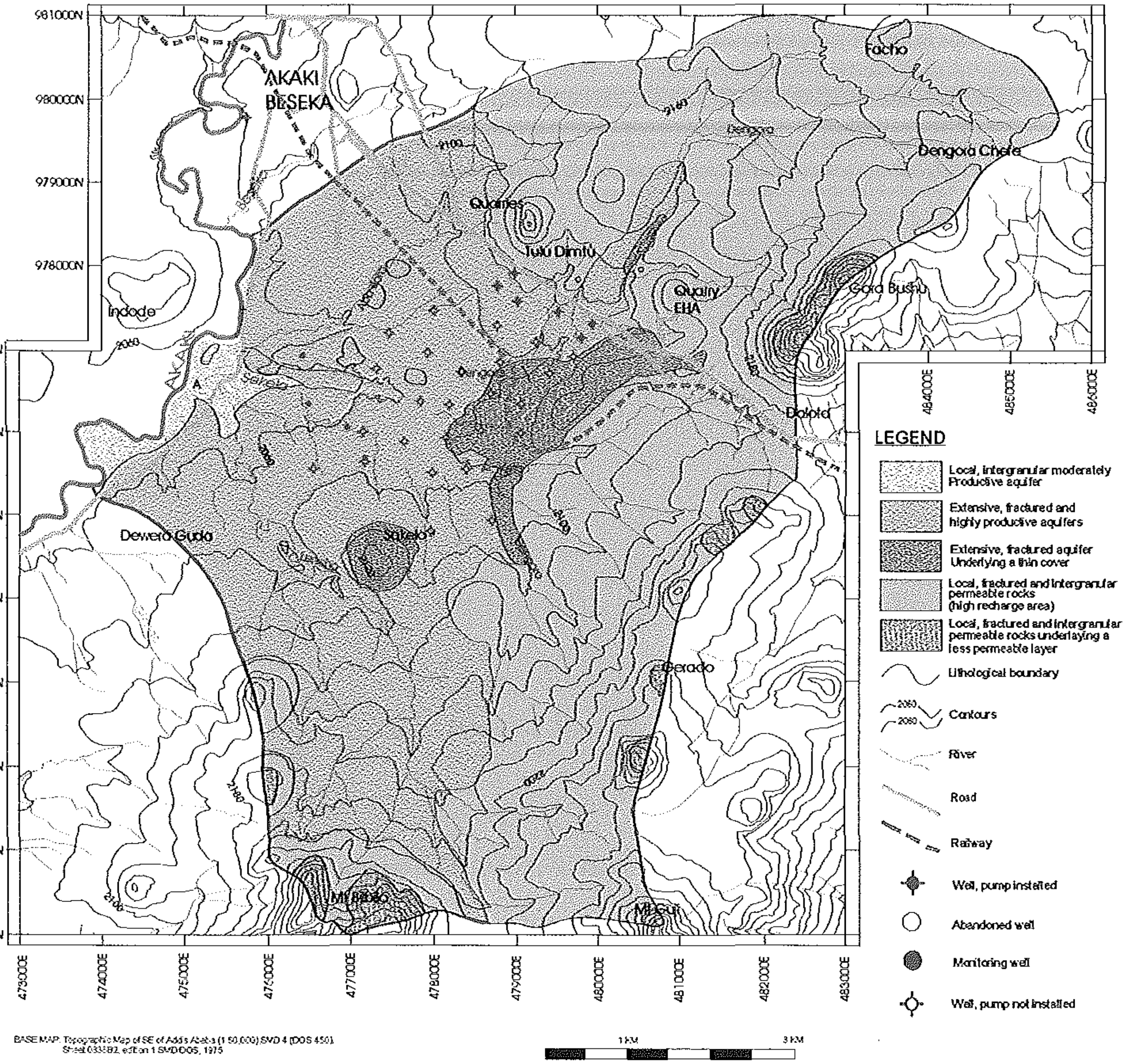
The scoracious basalt which are observed at the top of some of the scoria cones have a thickness ranging from 10 m north of Mt. Bilbilo to 90 m in Mt. Bilbilo. These are vesicular rocks which are not affected by tectonic stress. In some case the vesicles are filled by secondary minerals like calcite. Since the pores are not interconnected, this unit is less permeable.

4.2.3 Alluvial sediment

The alluvial sediment occurs along Akaki river and in small area along Sekelo stream. The exposed thickness is around 5 m along Akaki river. It is poorly sorted varying in grain size from sand to gravel. This sediment is highly porous and has intergranular permeability. Because of the limitation to get borehole log, it is not possible to know the maximum thickness of the sediment. However, based on grain size, sorting it is proved to be a good aquifer. Since it is concentrated only in patches along the river, this can be classified as a localised aquifer with intergranular porosity. This may represent a reasonable aquifer for extracting shallow water from large diameter hand dug wells. But one should always keep in mind the higher danger of contamination in shallow wells from the Akaki river.

HYDROGEOLOGICAL MAP OF AKAKI SUBBASIN (SEKELO)

Scale: 1:75,000



BASE MAP: Topographic Map of SE of Addis Ababa (1:50,000) SVD 4 (DOS 450) Sheet 0338B2, edition 1 SVD/DOS, 1975

Fig 4.2: Hydrogeological map of Akaki subbasin Sekelo

4.2 4 Soil cover

Knowledge of the soil cover of an area is important to understand the flow of water and contaminant transport. Soil consists of mostly of mineral grains of varying size as well as varying amounts of organic matter. The porosity and permeability of the soil is a function of both the soil texture and structure. The clay fraction of the soil consists of mineral particles less than 2 μm in diameter. They are consist of mainly secondary mineral formed by weathering. Clay minerals have an unbalanced negative electrical charge at the surface. Electrostatic attraction exist between the surface of clay particle, the soil water molecule, and the solute dissolved in the water. This reactive property of the clay allows them to absorb large amount of water and ions. This results swelling of clay when wet and shrink and crack when dry (Fetter, 1999).

The soil in the project area is clay which is developed by chemical and physical weathering of volcanic rocks. The soil in the area vary in thickness from 1 m in bh07 to 20 m in bh11. The colour also vary from black to brown. The black colour of the soil is because of decomposed organic material. The brown colour may indicate that it is the product of weathering of scoria. As explained above this soil has the property to absorb water and swell. This property is good to prevent contaminant transport into the groundwater.

4.3 Groundwater exploration

4.3.1 Objective

Legedadi and Gefersa surface water reservoirs in conjunction with groundwater have been supplying the population and industries in Addis Ababa and Akaki. The growing number of population and industries in Addis Ababa and Akaki alleviate the need to develop water resources. Since the city of Addis Ababa is situated near the water divide, streams with large catchment areas are absent. This limits surface water development in Addis. Other limiting factors are dam siltation and pollution. Regarding groundwater the yield of the aquifers in Addis Ababa is rather small to supply large population and industries. Feasibility studies concluded that the area between Akaki and Debre Zeit will provide a good amount of groundwater for Akaki and Addis Ababa (Tesfaye Chernet, 1993).

To resolve the shortage of water and to provide the people with clean water, deep wells were drilled in Akaki area. From 1991 to 1996 four deep wells for Akaki town water supply and four monitoring wells were drilled and constructed by WWDE as contractor and AAWSA as a client in Akaki Well Field D. AAWSA implemented Addis Ababa Water Supply Project Stage IIIA to detect and exploit further groundwater, twenty five deep wells have been drilled and constructed by COMPLANT from 1996-97 in the same well field.

4.3.2 Location of wells

Akaki Well Field D is located 20 km south-east of Addis Ababa along Debre Zeit road. The wells are found in the area between 476000 to 480500 E and 974700 to 978000 N in UTM reference grid (Figure 4.3) covering an area of around 15 km^2. The water wells in Metal Factory (MF), Spare Parts (SP) and Sidamo Awash village (SA) are taken in to consideration for water quality and isotope analysis. Boreholes EP4 to EP8 are Akaki town Water Supply Wells. The wells bh01 to bh26 are Addis Ababa Water Supply Wells. In this well group there is no bh15. Borehole bh03a and bh05a were abounded as they were found to be low yield and dry borehole, respectively. Instead of these two boreholes, bh03b and bh05b have been drilled. Four observation wells mw01 to mw04 are found at the vicinity of Akaki river.

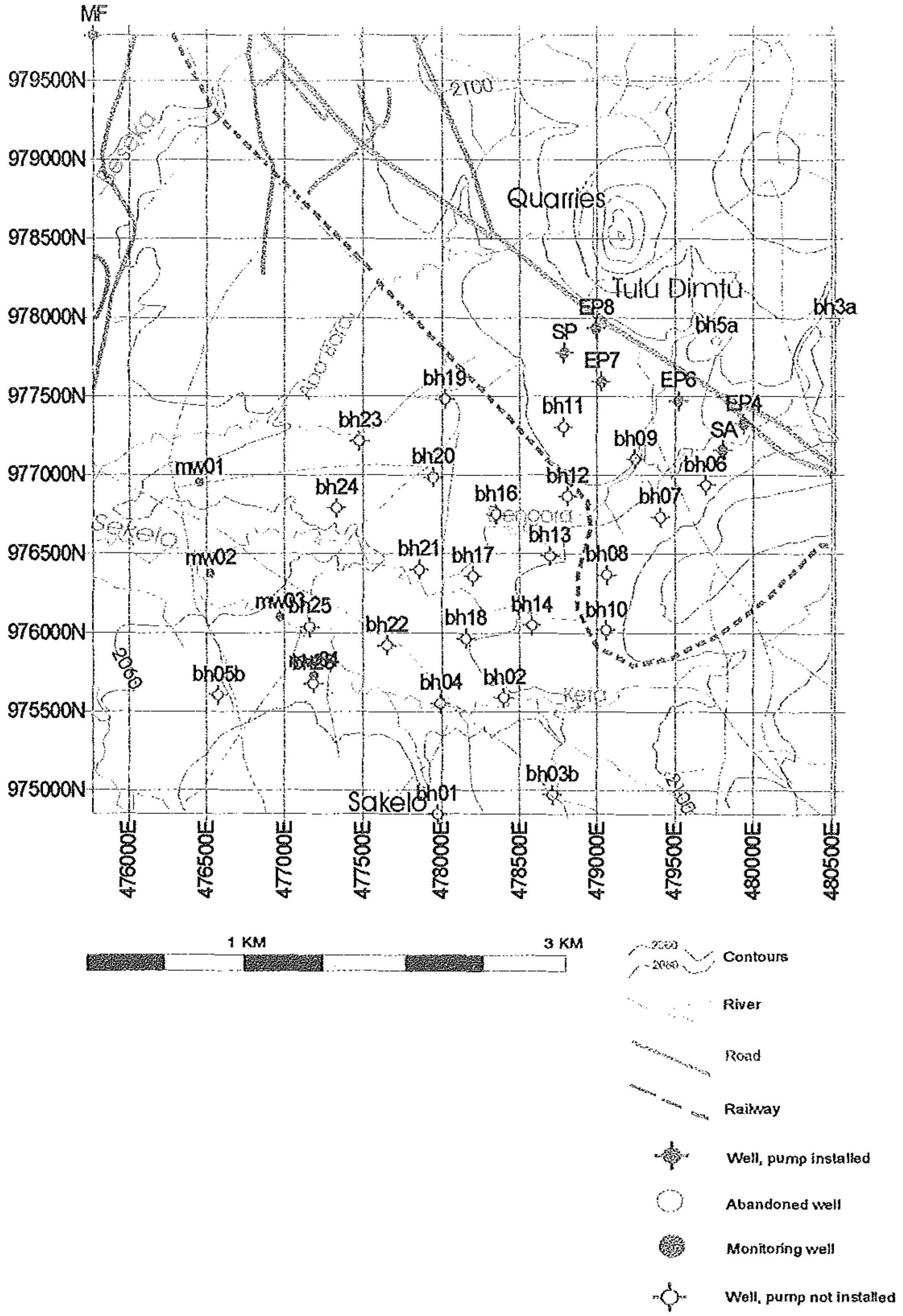


Fig. 4.3: Location of boreholes.

4.3.3 Well construction

Drilling was carried out using a percussion drilling machine Sankyo SM-22T for EP4 to EP8. Drilling rig Model SPC-300H is used for drilling bh01 to bh26. Monitoring well drilling activity was done using DTH drilling system by Cylone TH-60 and Porta rig type. The wells drilled for water supply of Akaki and Addis Ababa have depths ranging from 120 to 170 m. The diameter of these wells is 24 in from the ground surface to a depth of 10 to 25 m in different boreholes, 17.5 in in the middle part and 12.5 in from around 80 to 100 m till the bottom of the borehole. Borehole EP4 is an exception which has a diameter of 19 in from the ground surface to a depth of 4.7 m and 15 in from 4.7 m to the bottom of the well at 120 m. The observation wells have diameters of 12.25 in from the ground surface to a depth of 6 or 10 m. In the lower part the diameter vary from 9.6 to 8.5 in.

Mild steel casings and stainless steel Johnson screens are installed for the water supply wells. Screens are perforated pipes which guarantee a favourable entrance velocity of the water. Casings are pipes without perforations that protect the well from collapsing. They are installed between and above screens in positions where no water is caught. Boreholes EP6 to EP8 and bh01 to bh26 have surface casings of 20 in diameter. The position of the 14 in casings varies in different boreholes depending on the position of the aquifer. The small diameter 8 in casings is usually placed in the lower part of the wells. Again EP4 represents the exception due to the smaller diameter of the borehole. The observation wells have steel surface casings of 8.6 in or 10.8 in diameters. Below the protective surface casing polyvenylchloride (PVC) pipes are placed. The diameter of the screens is the same as the one of the casings depending on their depth location. The mild steel casing and Johnson screens are connected using dielectric joints.

Cementing or grouting of the upper section of the well is employed to seal the space between the surface casing and the wells, protecting them against contamination from surface water. An example of the construction is shown in figure 4.4. EP4 to EP8 are provided with a well head (fig.4.5).

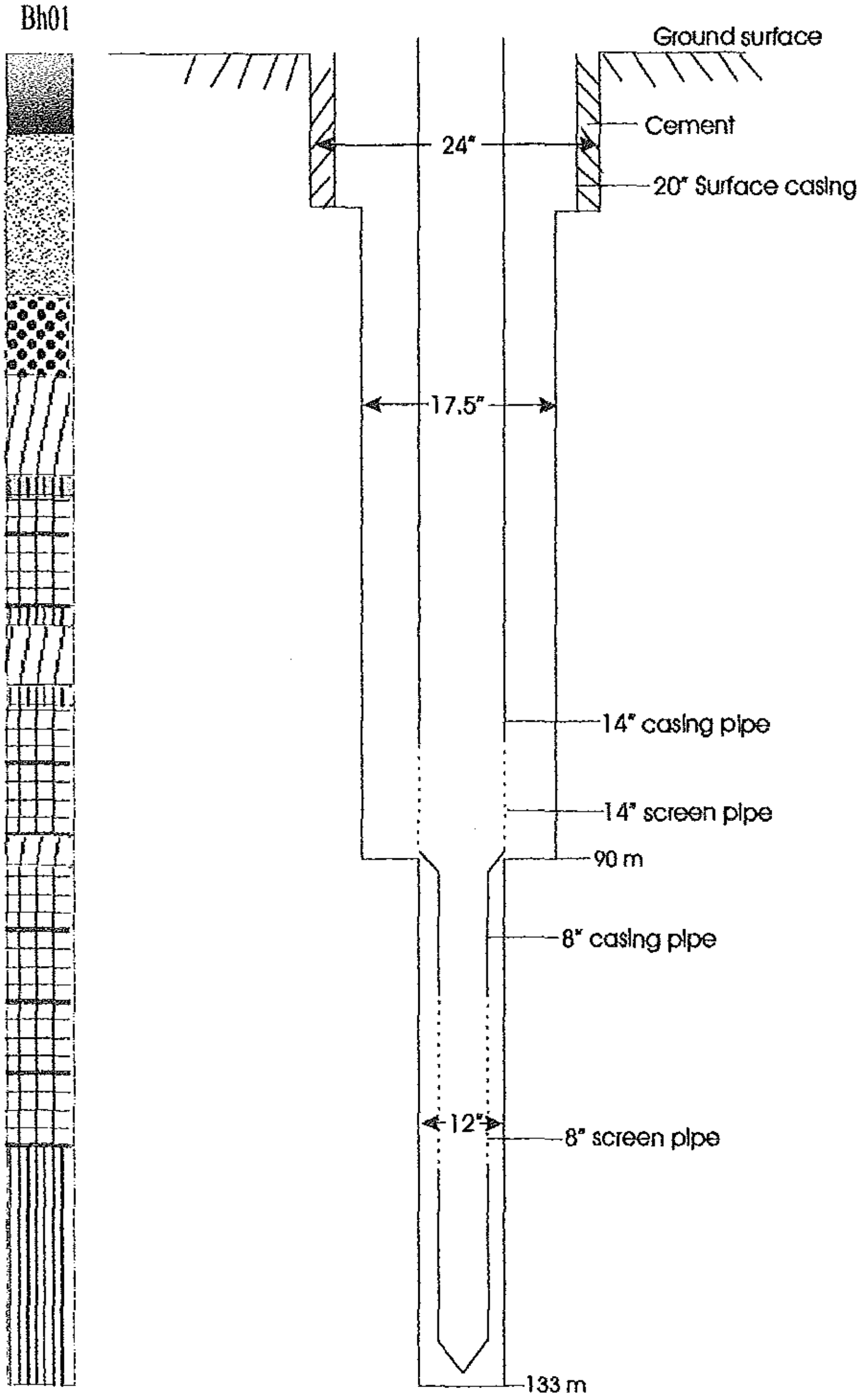


Fig. 4.4: Construction of bh01. " represents the unit in inch. The legened for the geologic log is shown in appendix 1 (modified, AAWSA)

Following the construction, a well development was undertaken. This has the purpose to improve the productivity of the wells by removing pluggings and enables sand free water lifting. In this case two different development methods are used: 1. Simple development and 2. Air lift method with air compressor.

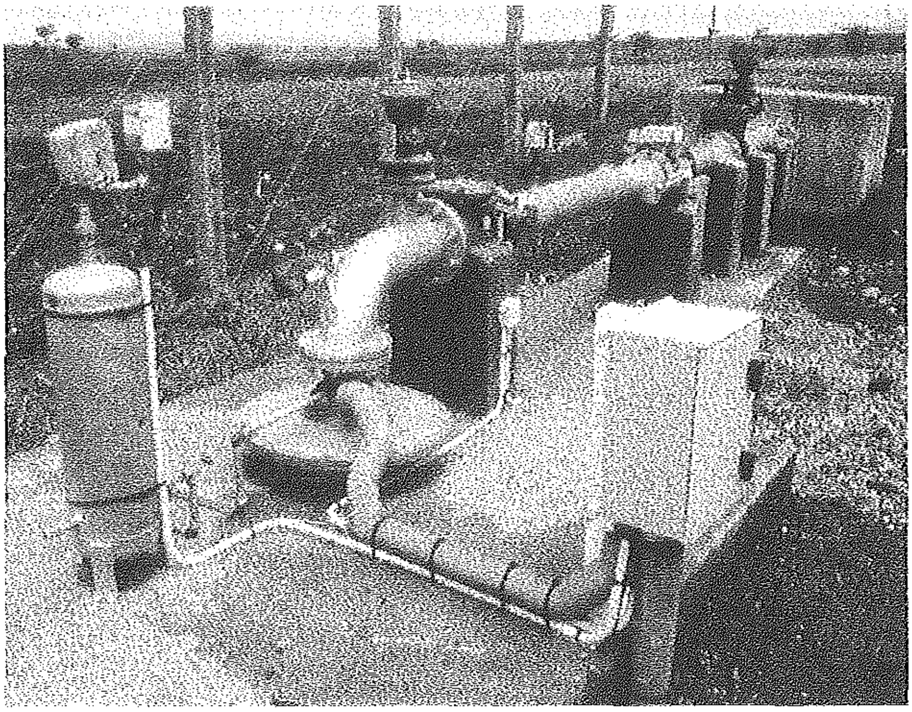


Fig. 4.5: Well head and distribution pipe of borehole EP4.

4.4 Water level data and the piezometric map

A problem with collecting hydrogeological data in the well field is that the wells have no access for water level measurements, either because a submersible pump is installed or because the borehole is blocked. Therefore, water levels are taken from borehole records. These data refer to the levels at the time of well completion, which is between June 1995 and end of 1997. This introduces errors in defining piezometric contours, because of temporal variations in groundwater levels. In addition to this, interference of wells during pumping produces error in the water level.

The scale of such errors may be found by comparing borehole water level at the time of completion with levels measured when the borehole was used as observation well during pump test. Table 4.1 shows these variations in four boreholes. This table indicates the difference in water levels measured in different time ranging between 0.1 to 3.5 m. The first borehole mw03 shows variation in water level of 0.4 m in sixteen months. A difference of 3.5 m is indicated in mw04 in fourteen months. This variation can be because of seasonal and time variation of groundwater level. In addition to this, the pumping of bh25 which is 300 m away, two days before this measurement is done. This effect in water level because of pumping in bh25 is also seen in bh22 and bh26. Borehole bh26 shows a variation of 0.3 m in ten months time. The same well shows a lowering of 0.1 m in two days after pumping test has been done in bh25. Lowering of 0.1 m is observed in bh22. However, complete recovery of both wells bh22 and bh26 is seen in the recovery record of bh25. So this difference in the level may be measurement error. While these differences are significant, such temporal variations are large when compared with insignificant spatial variations in topography and water level geometry encountered in this area. Therefore, this produces error when considering groundwater movement in this scale.

Other errors are introduced into piezometric map construction by using borehole static water level which represents a local averaging of several piezometric surfaces where different aquifers are intersected by a borehole (Allen et al., 1989). This effect may be seen in bh16 which has the lowest water level and transmissivity in the well field. This shows that this well intersects a low permeability local aquifer compared to the other boreholes.

Well name	**Measurement date**	**Static water level (m) (below ground surface)**
mw03	20/01/96	41.0
mw03	05/07/97	40.6
mw04	06/03/96	47.0
mw04	06/05/97	50.5
bh22	04/05/97	47.8
bh22	08/05/97	47.9
bh26	08/07/96	51.0
bh26	04/05/97	50.7
bh26	06/05/97	50.8

Table 4.1: Borehole water level comparisons.

Because of the above mentioned reasons, it is not easy to show the actual local groundwater flow direction. Therefore, it is chosen to present the static water level in each well points (Figure 4.6). However, for the shallow groundwater the regional groundwater movement is inferred to be sub-parallel to the general surface topography. Regional flow systems have the recharge area in the basin divide and the discharge at the valley bottom (Fetter, 1994). In the study area the scoria cones surrounding the area are the recharge area and the river valley is the discharge area. Hence, the regional flow direction is anticipated to be from all direction to the direction of the river.

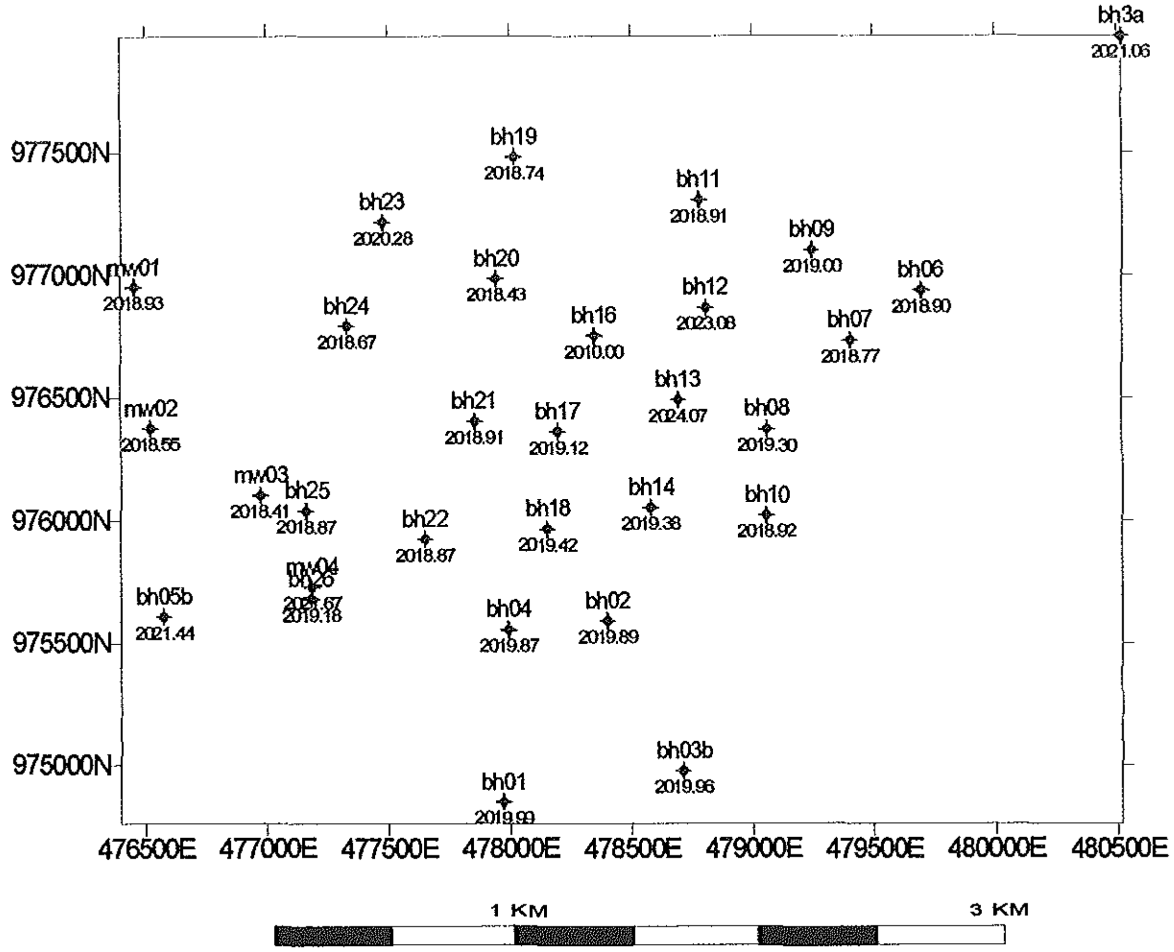


Fig. 4.6: Water level record in wells.

4.5 Aquifer properties

4.5.1 Transmissivity and storage coefficient

A problem in the determination of aquifer transmissivity and storativity is that the standard field hydrogeological test of a carefully monitored pumping test with observation wells has not been undertaken when water wells have been drilled. In some cases recording of the recovery data have been stooped after a short period, before full recovery of the well. These make it difficult to evaluate the data.

AQTESOLV for windows computer program has been used for the analysis of the aquifer properties using pumping test data. While most of the boreholes are semi-confined, leaky aquifer solutions have been chosen as the best solution for these aquifers. Moench (1985) type curve solution is used for the analysis of most of the boreholes. Where early time pumping data are assumed to represent the aquifer property Hantush (1960) type curve solution is employed. Since these two solution methods assume the confining beds have storage coefficient, these best fit to the aquifer in this area.

Since for the calculation of transmissivity and storativity aquifer thickness, radius of the well and casing, as well as screen position is important. The analysis of these properties have been performed only for those boreholes which have geologic log, well construction and electrical logs. Constant-rate pumping test is utilised to obtain the aquifer properties. In some boreholes recovery data recorded after constant pumping test are used to check the results from actual pumping test. Since no observation wells are used (except bh25) the data from recovery provide good basis only for transmissivity.

In using the above solution methods, units were chosen: meter for drawdown and minute for time. Aquifer data such as aquifer thickness is observed from the logs and the ratio of vertical to horizontal hydraulic conductivity is assumed to be 1. Wellbore radius and casing radius have been entered. Pumping well penetration data such as the position of the screen is given. In all the boreholes fully penetrating well is assumed. Pumping period data is defined by entering a starting time and pumping rate for the period. As the pumping wells are taken as observation well, observation well penetration data is the same as pumping well data except (bh25). Time-drawdown data are entered in the observation data box. After importing data from an aquifer test, visual or automatic curve matching methods have been accessed to get the best fit of the plot with the curve. After statistical evaluation of the aquifer test the results of transmissivity (T) in m^2/day and storage coefficient (S) are displayed. The time-drawdown curves and values of transmissivity and storativitys are given in Appendix 2. The strict validity of these solutions are questionable. While factors such as partial penetration and anisotropy are likely to be common.

The storativity values range from $2.4*10^{-4}$ to 0.1 and the transmissivity value ranges from 389 in bh16 to 21600 m^2/day in bh07, bh08 and bh26. The transmissivity values are converted to hydraulic conductivity by dividing T with aquifer thickness. The calculated hydraulic conductivity values vary between 7.4 to 674.8 m/day. These values lie in the range of permeable basalt according to the representative values of hydraulic conductivity for various

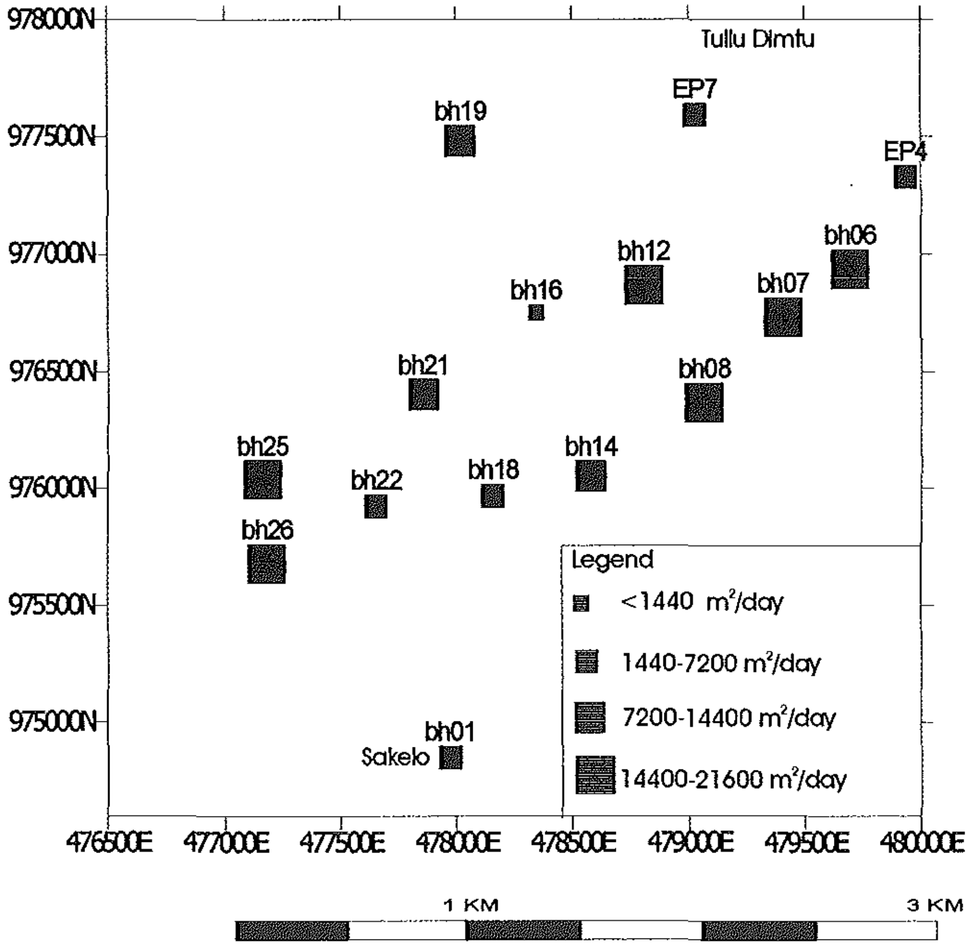
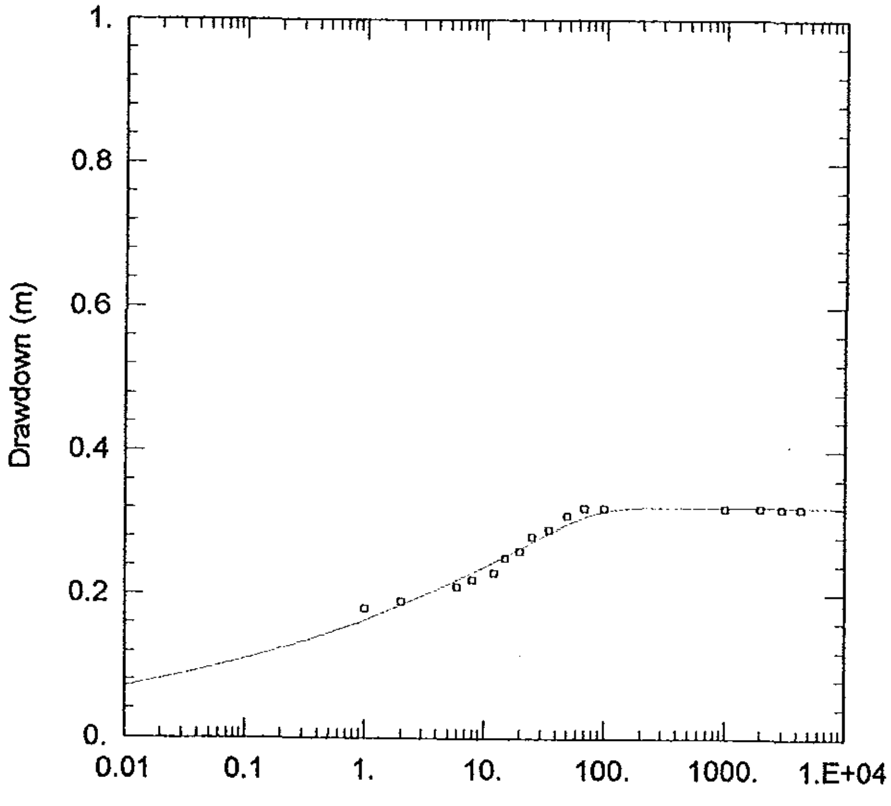


Fig. 4.7: Transmissivity map

rock type given by Domenico et al., (1990). Map of the transmissivity of the area is given in (Figure 4.7).

Hydrogeological conditions affect the time-drawdown graphs. One of these conditions is the recharge boundary condition. The drawdown will stabilise when recharge within the zone of influence of pumping well equals the rate of discharge of the well. This condition can be seen in many of the boreholes as an example bh18 is given in figure 4.8. The first part of the curve in this figure shows that the cone of depression was enlarging during the first 160 minutes of pumping. After 160 minutes, the cone of depression, or the area of influence of the well encountered a source of recharge. In the second part of the curve, the rate of recharge in the area of influence was sufficient to equal the pumping rate, resulting in stabilised water level. As a result, the second part of the curve is horizontal.



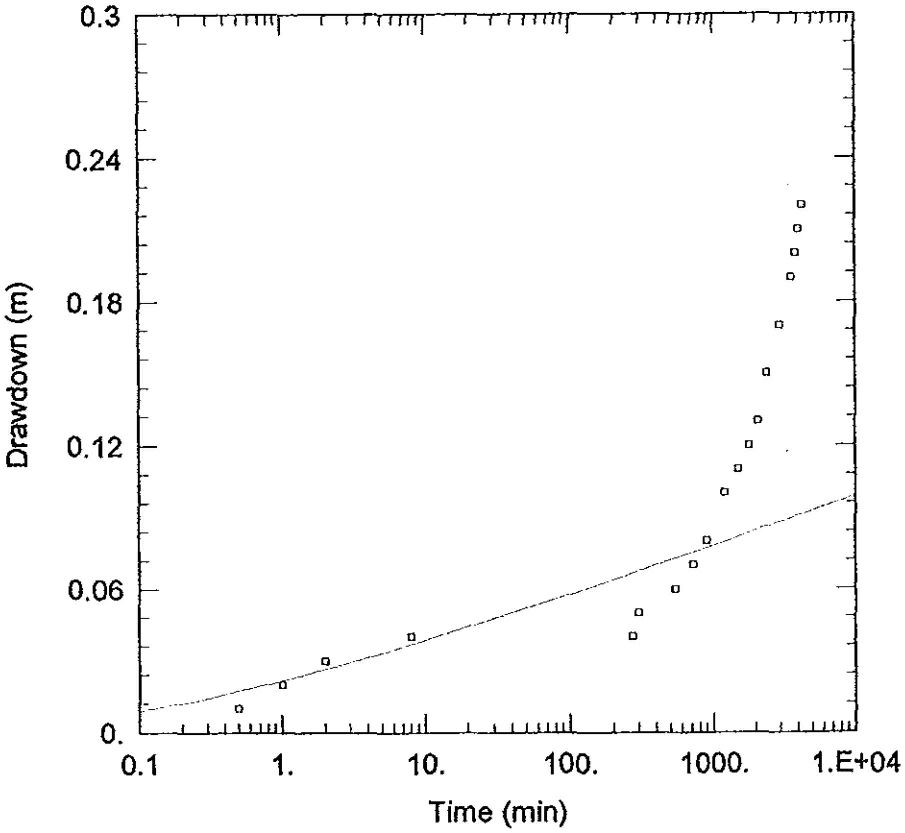
Solution: Moench

T = 5386 m^2/day

S = 0.133

Fig.4.8: Recharge boundary condition bh18

The second condition which affects the time-drawdown graph is impervious boundary condition. Under basic assumption water flows in equally from all directions toward a well. When the expanding cone of depression encounters an impervious boundary on one side of the pumped well, it expands no further in that direction and no additional water can be supplied from that locality. The cone must expand and deepen in all other directions to maintain the yield (Driscoll, 1995).This boundary causes the slope of the drawdown plot to steepen, as shown in EP4 (Figure 4.9). In this case the early data is used for the calculation of the aquifer coefficients. Evidence of boundary effect is seen in this graph after 300 minutes of continuous pumping. The last part of the time-drawdown plots can be extended to predict water levels after longer period of continuous pumping. The presence of impervious boundary in this borehole can be proved from the recovery data, that after pumping has been stopped, the well didn't show any recovery up to 360 minutes.



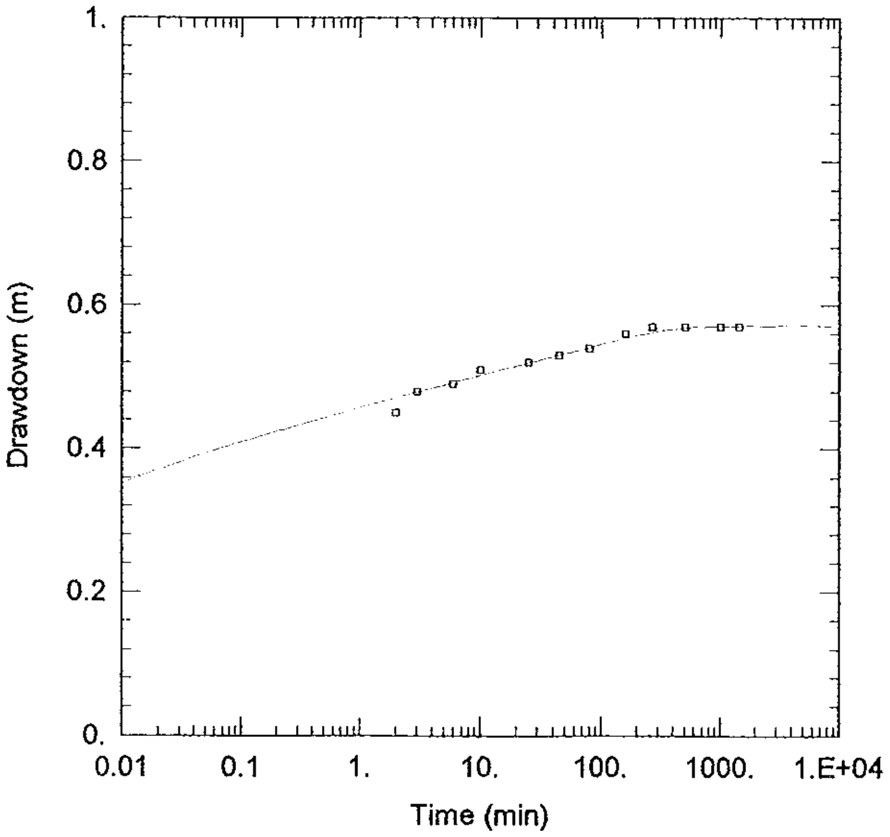
Solution: Hantush

T = 6532 m^2/day

S = 0.042

Fig. 4.9: Impermeable boundary condition EP4

The other condition that affect time-drawdown graph is casing storage. Early pumping test data reflect the removal of water stored in the casing. When pumping begins, water in the casing is removed first. As the water level in the casing falls, water begins to enter the well from the surrounding formation. Gradually, a greater percentage of the well yield will be from the aquifer. The duration of the storage effect varies depending on the well diameter and specific capacity (Driscoll, 1995). In addition, at the initial stage of pumping the discharge is derived from the disturbed part of the aquifer immediately surrounding the well. Figure 4.10 bh12 shows in the early 3 minutes a drawdown of 0.49m, this can be the casing effect. Then the drawdown reaches 0.57 m at 240 minutes, this part of the curve represents the aquifer characteristic of the borehole. The effect of casing and well storage cannot be ignored in all the borehole analysis.



Solution: Moench

T = 14875 m^2/day

S = 0.000438

Fig. 4.10: Casing and well storage effect in bh12

Chapter Five

Hydrochemistry and Stable Isotope Hydrology

5.1 Introduction

The predominant water type in Ethiopia based on the dominant anions are bicarbonate, sulphate and chloride types (Tesfaye Chernet, 1993). The salinity of the groundwater in the country is classified in to four groups: areas with total dissolved solids (TDS) less than 500 mg/l, TDS 500 to 1500 mg/l, TDS 1500 to 3000 mg/l and TDS greater than 3000 mg/l. Generally, the salinity increases from highlands to lowlands and the highlands are characterised by bicarbonate type water. The analysis of the water in the project area gave TDS less than 1500 mg/l. The evaluation of the analysis result shows that the water type is bicarbonate.

It has been discussed in the previous chapter that deep groundwater wells have been drilled for the water supply of Addis Ababa and Akaki town 20 km SE of Addis Ababa along Debre Zeit road (in the vicinity of Akaki river). As many of the tributaries of the Akaki river are flowing through the city of Addis Ababa which is highly populated, faecal pollution and sewage are strongly elevated . Many factories are located along Addis Ababa-Debre Zeit road near the Akaki river. Therefore, pollution of the river from industrial discharge is expected. Contamination by faecal pollution is confirmed by high number of total coliform bacteria detected in the analysis of the river (Anteneh Girma, 1994). In this river water which is contaminated by sewage, the dissolved organic carbon (DOC) and chemical oxygen demand (COD) are anticipated to be high and chloride, sulphate, nitrate, ammonium, phosphate and borate are the main contaminant. As borate is used in soap, it is the primary pollutant near dense settlement. In addition to sewage, the runoff from agricultural land increase the concentration of nitrate, ammonium, phosphate and also higher concentration of calcium are expected. The increased amount of these ions due to sewage and agricultural discharge is proved from the result of the analysis. The effluent from Akaki Textile Factory may increase the DOC content. Zinc (Zn), copper (Cu), chromium (Cr) and light hydrocarbons (LHC) are presumed pollutants. The DOC and COD concentration of the water is also affected by the factories like Addis Tannery and Akaki Edible Oil. The LHC is also the expected contaminant in edible oil factories (Hölting, 1989). Chromium is the main contaminant in Addis Tannery. This is confirmed by high concentration of this ion from the analysis of the river water near the factory (personal communication, Chemistry Department, Addis Ababa University). Wells drilled nearby the strongly polluted river may not yield water potable for drinking due to the mixing of the river water with groundwater. Current drinking water standards which include national primary and secondary drinking water regulations from USEPA 1998 is given in appendix 3.

The results of the analysis have been used to classify the type of water and to determine the origin of the water. Stable isotope analysis has been carried out to comprehend the interaction between the groundwater and the river water.

5.2 Sampling and analysis

5.2.1 Sampling

Since the boreholes from bh01 to bh26 were blocked, water analysis data for these boreholes were collected from AAWSA 1997. Chemical analysis data were also collected for EP4 to EP8 from the same authority 1996. Samples were collected from Akaki Water Supply Wells EP4-EP7, Spare Part Factory (SP), Metal Factory (MF), Sidamo Awash village (SA) and

Akaki river in three localities (RB, RI, RE). The location of the water analysis is shown in figure 5.1.

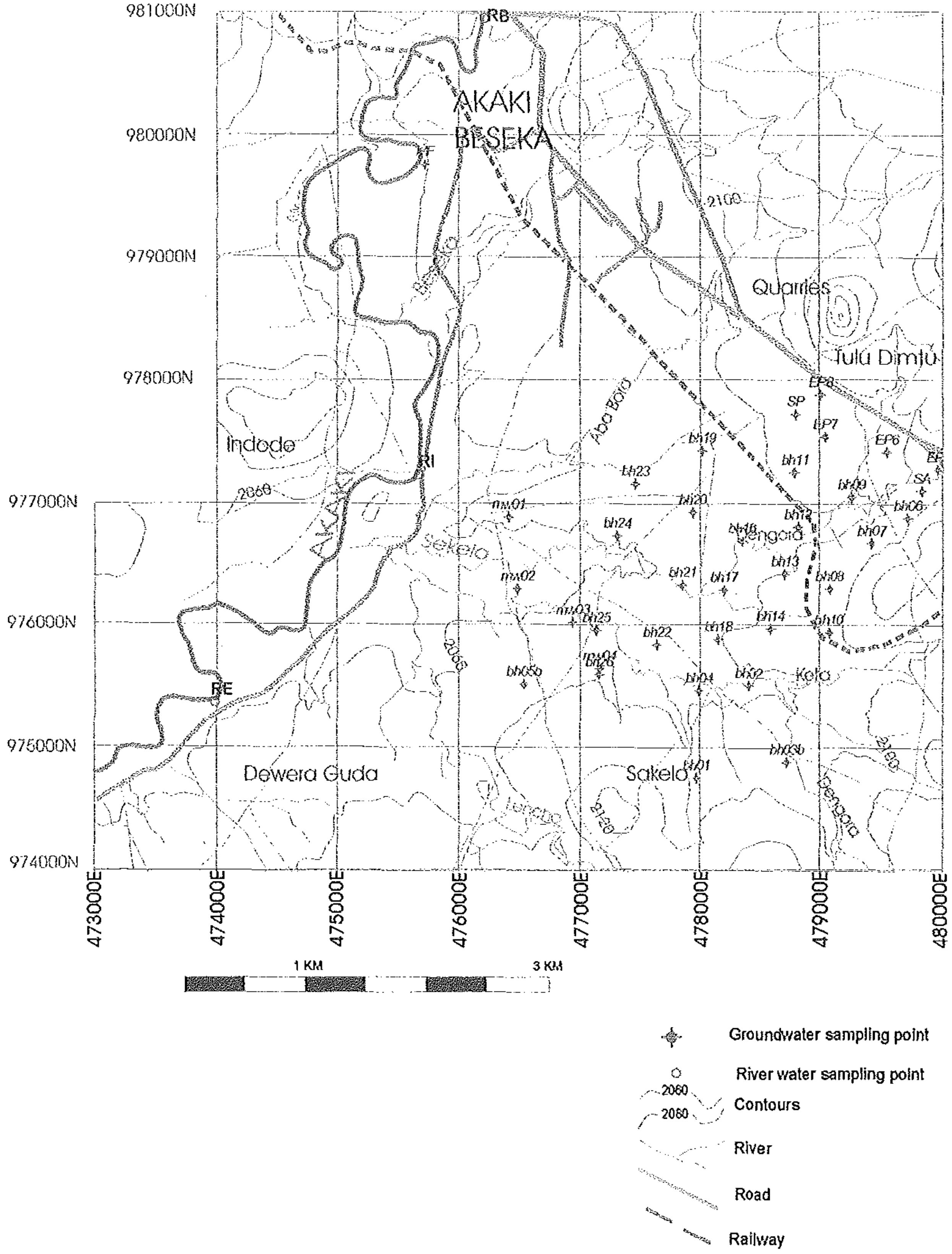


Fig. 5.1: Location of groundwater and river water sampled points

Water quality sampling was performed in June 1998 in one week time. Samples intended for chemical analysis were collected using 1 litter glass bottles. The bottles were rinsed with sample water prior to collecting. Samples from EP4-EP7 were taken from the site. These wells were pumped two days before sampling. This ensures that stagnant water is not collected which is affected by interaction with the casing. Water was collected from the tap in MF and SP. Sample from SA is also taken from the site. This well is pumped every day for the supply of the Sidamo Awash village. After collecting the samples were stored in cool dark place for 5 days to eliminate biological activity.

Samples for oxygen-18 and deuterium stable isotopes analysis were filtered through a 0.45μ millipore filter paper and collected in 100 ml plastic bottles with plastic screw caps. These bottles were also prerinsed with sample water. To prevent evaporation which enriches the residual water with heavy isotopes the bottles were filled completely and closed promptly. These samples were also stored in cool place for two months.

5.2.2 Measurement

Measurements of temperature, electrical conductivity and pH were made at the time of sampling. The conductivity meter used to measure the electrical conductivity (ec) was first calibrated with 0.01 M KCl which has ec value of 1288 at 20.4°C. The pH is determined using a pH meter which is calibrated with a buffer standard that has pH value of 4 units. The water analysis data from AAWSA were analysed by the National Research Institute of Health from 1996-97.

The chemical analysis for the samples collected during the project were accomplished by Ethiopian Geological Survey Water Laboratory. All major cations and trace or heavy metals analysis were performed by Atomic Absorption Spectrometry. Light of special wavelengths, depending on the specific compound which will be analysed, is absorbed by the atoms in a flame. The light quantity absorbed from the sample, is dependent on its concentration and can be measured. The anions such as HCO_3, Cl are determined using titration methods. For the determination of fluoride an ion selective electrode is used. The other anions SO_4, and NO_3 as well SiO_2 and HBO_2 are analysed by Absorption Spectrophotometer. The wavelength of the light, which is beamed through the sample solution is varied with time and the absorption-wave curve is registered. The wave length of the maximal absorption is dependent on molecular structure and therefore it is a characteristic value of a special substance. The absolute value of the absorption depends on the concentration of the substance.

Stable isotope analysis was carried out in the Mineralogy Laboratory at the University of Tübingen, Germany. Both isotopes were measured with an Isotope Ratio Mass Spectrometer. The analysis of δ^2H is performed on the hydrogen gas obtained (in glass tubes) through high temperature (430°C) reduction of water (3µl probe) by specially prepared zinc.

$$Zn + H_2O \rightarrow ZnO + H_2$$

Analysis for $\delta^{18}O$ was done on carbondioxide that has equilibrated with the water sample at a constant temperature of 25°C. Normally equilibration is executed for 6 hours. 5 ml of water was added to the reaction vessels, then evacuated by pumping through capillary tubes connected to the mass spectrometer. One measurement lasts 20 to 30 minutes. The isotope exchange reaction is as follows:

$$CO_2^{16} + 2H_2O^{18} \rightarrow CO_2^{18} + 2H_2O^{16}$$

5.3 Water chemistry

5.3.1 Results

The water sampled fall into two main groups: groundwater and river water. The former category includes water whose composition is mainly derived from water-rock interaction, while the later comprises waters more affected by human impact and environmental-climatical factors.

Results of chemical analysis for the groundwater from AAWSA 1996-97 and chemical and isotopic analysis of groundwater and river water during the project are reported in table 5.1 and 5.2, respectively. The major chemistry of the groundwater and the river waters are summarised in table 5.3 and 5.4, respectively. From the tables 5.1 and 5.3, it is apparent that the groundwater is dominated with alkali earth and bicarbonate ions and relatively high sodium concentrations. All the waters are saturated with respect to silica. The analysis are typical of igneous terrains, where the reaction of the hydroxide which is released from the weathering of silicate minerals with carbondioxide produces the main anion HCO_3^-. Only trace amounts of chloride, fluoride and sulphate minerals are present hence the low amounts of these ions and relatively low total dissolved solid (TDS) averaging 444 mg/l. The result shows that the pH is similar for most of the groundwaters and averages 7.2 pH units which is typical of diluted bicarbonate water. Oxygen contents were measured for most of the groundwaters and have average concentrations of 8.46 mg/l. At 30°C in fresh water the equilibrium dissolved oxygen value is 7.45 mg/l (Hem, 1992). Therefore, the groundwater is saturated with oxygen for the temperature range between 22°C to 24°C. Low concentrations of total iron due to low solubility of this metal in the prevailing pH and oxidising condition.

Site	Temp (°C)	pH	EC at25°C (µS/cm)	CO_2	O_2	Bicarb.Alk. as $CaCO_3$	Hardness as $CaCO_3$	SiO_2	K	Na	Mg	Ca	Fe total	NH_4	PO_4	F	NO_2	NO_3	Cl	SO_4	HCO_3	TDS
bh01	23	7.2	481.5	28.1	8.46	240	208	65	4.62	27.2	23.4	44.9	0.17	0.06	0.02	0.4	0.05	14.4	14.2	n.d.	292.8	422.22
bh02	23	7.3	462.8	28.5	8.8	240	212.6	68.3	4.3	23.8	23.4	46.5	0.14	n.d.	0.03	0.38	0.02	16	14.2	n.d.	292.8	421.57
bh03b	23	7.3	462.8	28.5	8.8	240	208	67.1	5.3	23.8	24.3	43.3	0.04	n.d.	0.04	0.3	0.02	11.2	11.3	n.d.	292.8	412.4
bh04	22	7.2	477.6	29.1	8.48	230	200	65.8	4.6	27.2	21.4	44.9	0.02	0.01	0.07	0.38	0.16	14.3	14.2	n.d.	280.6	407.84
bh05b	24	7.3	385	28.1	8.89	200	160	70.4	4.3	25.5	11.6	44.9	0.05	n.d.	0.07	0.6	n.d.	3.2	14.2	n.d.	244	348.42
bh06	23	7.7	485	13.2	8.5	252	226	59	4.2	24.5	27.2	45.7	0.04	n.d.	0.03	0.35	0.02	18.6	9	6.6	307	443.24
bh07	23	7.2	493	13.6	8.6	256	224	59	4.2	26	27.7	44.1	n.d.	n.d.	n.d.	0.32	1.5	13.7	8.5	7.6	312.3	445.92
bh08	23	7.2	464	26.5	8.62	250	232	64.3	3.63	27.2	29.2	44.9	n.d.	n.d.	0.06	0.24	0.01	25.7	17	n.d.	305	452.94
bh09	24	7.2	512	13.5	8.6	268	235	62	3.6	27.2	27.7	48.5	n.d.	n.d.	0.04	0.42	0.02	16.7	8.7	7	327	466.88
bh10	23	7.2	478.7	29.8	8.22	250	216	62	3.96	30.6	28.2	40	n.d.	n.d.	n.d.	0.23	0.13	9.2	14.2	7.4	305	438.92
bh11	22	7.2	516	27.1	8.28	240	224	64	2.97	30.6	26.3	46.5	0.02	0.05	n.d.	0.32	0.01	21.2	11.3	17.5	292.8	449.57
bh12	22.5	7.2	508.2	22.5	8.3	280	248	66.5	3.96	27.2	24.32	59.3	0.02	n.d.	0.03	0.52	0.01	9.8	11.6	6.5	341.6	484.86
bh13	24	7.2	457.5	13.5	8.6	230	204	68.3	4.3	23.8	23.4	43.3	0.03	0.01	0.04	0.38	n.d.	12	14.2	n.d.	280	401.46
bh14	23	7.2	476.4	28.2	8.3	270	228	66.5	5.94	27.2	26.3	48.1	0.01	n.d.	n.d.	0.7	n.d.	n.d.	9.2	6.58	329.4	453.43
bh16	22.5	7.2	542.4	26.5	8.3	270	240	70	5.3	27.2	24.4	56.1	0.12	n.d.	n.d.	0.39	0.15	3.9	14.2	5.35	329.4	466.51
bh18	23	7.2	436.6	26.5	8.62	252	224	70.4	4.6	23.8	26.8	45.7	0.02	0.17	n.d.	0.3	3.5	11.4	11.3	n.d.	307.4	434.99
bh19	23	7.2	602.3	28.1	8.46	260	240	68	3.3	30.6	25.3	54.5	0.07	n.d.	n.d.	0.26	0.03	13.3	14	16.05	317	474.41
bh20	23	7.2	398	28.1	8.46	200	164	71.3	4.6	23.8	13.6	43.3	0.03	n.d.	0.03	0.6	0.01	4.9	14.2	n.d.	244	349.07
bh21	23	7.2	512	29.8	8.23	240	232	68.5	3.96	27.2	24.3	52.9	0.03	n.d.	n.d.	0.35	0.11	13.8	14.2	26.75	292.8	456.4
bh22	22	7.2	494.2	29.1	8.48	240	220	67.5	4.3	27.2	23.35	49.7	0.09	n.d.	n.d.	0.39	0.69	13.7	14.2	7	292.8	433.42
bh23	22	7.2	462.8	29.1	8.48	250	228	74.2	2.64	18.7	19.5	59.3	0.04	0.04	0.04	0.5	0.13	1.33	14.2	n.d.	305	421.42
bh24	22	7.2	477.6	29.1	8.48	240	180	63.8	4.6	40.8	19.5	40.1	0.39	0.07	0.03	0.38	0.01	12.3	14.2	n.d.	292.8	425.18
bh25	23	7.2	494.2	28.7	8.23	240	220	69	4.3	27.2	23.4	49.7	0.08	n.d.	n.d.	0.4	4.2	9.4	14.2	8.85	292.8	434.53
bh26	23	7.2	476.4	29.2	8.21	240	224	76.5	3.96	27.2	23.35	49.7	0.01	n.d.	n.d.	0.55	0.01	12.3	12	7.4	292.8	429.28
EP6	n .m.	n. m.	475	n. m.	n. m.	248	216	60	3.1	28.9	26.3	43.3	n.d.	n.d.	0.04	0.43	0.01	16.3	8.2	6.4	302.6	435.58
EP7	n .m.	n. m.	469	n. m.	n. m.	228	190	51.3	4.6	35.7	28.2	29.7	0.02	0.02	0.03	0.29	0.04	16.4	12.7	13	278	418.7
EP8	24	7.3	496	21.2	8.1	248	196	57.4	3.3	36.6	23.6	39.7	n.d.	n.d.	0.04	0.45	0.02	16.4	9.2	7.9	302.6	439.81

Table 5.1: Chemical analysis data of groundwater samples. Unit is in mg/l unless otherwise stated. (AAWSA 1996-1997)

Remark: n.m. is not measured, n.d. is not detected

Site	Temp (°C)	pH	EC at 25°C (µS/cm)	CO_2	HBO_2	SiO_2	K	Na	Mg	Ca	Fe total	Mn	Cd
EP4	18.6	7.2	511	12	0.42	26	3	28	25	44	< 0.1	< 0.1	< 0.1
EP6	22	7.5	510	11	< 0.17	27	3	28	25	44	< 0.1	< 0.1	< 0.1
EP7	24.6	7.6	510	11	0.67	26	3	28	25	44	< 0.1	< 0.1	< 0.1
SP	19.5	7.8	557	13	0.67	28	3	31	22	54	< 0.1	< 0.1	< 0.1
MF	19	8	708	7	1.34	29	5	38	29	74	< 0.1	< 0.1	< 0.1
SA	20.2	7.5	697	18	< 0.17	30	3.3	26	25	78	< 0.1	< 0.1	< 0.1
RB	19.6	n. m.	465	11	< 0.17	16	11	31	8	44	0.4	< 0.1	< 0.1
RI	20.8	n. m.	455	13	0.67	17	11	30	9	43	1	< 0.1	< 0.1
RE	n. m.	n. m.	458	16	< 0.17	15	11	30	8	44	0.6	< 0.1	< 0.1

Table 5.2: Chemical analysis and isotopic composition of groundwater and river water samples collected during the project. Unit is in mg/l unless otherwise stated.

Remark: n.m. is not measured, < 0.1 and < 0.17 indicate below detection limt.

Site	Cr	Pb	Ni	Cu	Zn	F	NO_3	Cl	SO_4	HCO_3	TDS	δ^2H (°/₀₀)	$\delta^{18}O$ (°/₀₀)
EP4	< 0.1	< 0.1	< 0.1	< 0.1	1.3	0.31	15	8	6	306	436.61	-2.6	-1.39
EP6	< 0.1	< 0.1	< 0.1	< 0.1	0.6	0.3	15	9	5	307	436.9	-3.1	-1.404
EP7	< 0.1	< 0.1	< 0.1	< 0.1	0.5	0.3	15	9	7	301	432.8	-5.5	-1.601
SP	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	0.42	19	14	12	318	473.42	-5.35	-1.9
MF	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	0.4	18	19	23	411	617.4	-2.7	-1.8
SA	< 0.1	< 0.1	< 0.1	< 0.1	0.3	0.37	53	26	23	323	557.97	0.15	-1.025
RB	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	0.48	20	30	19	189	352.88	3.1	-0.781
RI	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	0.48	20	32	19	183	348.48	4.4	-0.599
RE	< 0.1	<0.1	< 0.1	< 0.1	< 0.1	0.48	15	32	21	183	345.08	3.2	-0.663

Table 5.2: continued

Ions	Average value (mg/l)	Range (mg/l)
K	4.1	2.97 – 5.94
Na	28.05	18.7 – 38.0
Mg	24.1	11.6 – 29.2
Ca	48.7	29.7 – 78.0
Fe	0.053	0 – 0.39
HCO_3	303.6	244 – 411
NO_3	14.4	0 – 53.0
Cl	13.08	8.0 – 26.0
SO4	7.16	0 – 26.75
F	0.39	0.24 – 0.70
SiO_2	60.9	26.0 – 76.5

Table 5.3: Range of concentrations and average values for the major ions in groundwater.

Ions	Average value (mg/l)	Range (mg/l)
K	11	11 – 11
Na	30.3	30 – 31
Mg	8.3	8 – 9
Ca	43.66	43 – 44
Fe	0.66	0.4 – 1.0
HCO_3	185	183 – 189
NO_3	18.5	15 – 20
Cl	31.33	30 – 32
SO_4	19.66	19 – 21
F	0.48	0.48 – 0.48
SiO_2	16	15 – 17

Table 5.4: Range of concentrations and average values for the major ions in river water.

The result of the river water analysis is shown in table 5.2 and 5.4. The river water has similar compositions as the groundwater with the dominant ions alkali earth and bicarbonate, indicating similar geologic environments. The river water contains lower TDS averaging 348 mg/l and the ions bicarbonate and magnesium averaging 185 and 8.3 mg/l, respectively. However this water displays a higher average concentration of potassium, chloride, nitrate, sulphate and phosphate. These differences in the river water and the groundwater is caused due to variations in the residence time and human impact. Higher concentration of iron is observable in the river.

5.3.2 Plausibility control of analysis

Under normal circumstance, the sum of cations equals the sum of anions in each solution. Hence the sum should be true for reported laboratory data and the deviation from such an equality indicate unreliability in the data quality. According to the principle of electroneutrality, the accuracy of the analysis can be examined by the following formula:

$$\text{Error (\%)} = \frac{\Sigma\text{cations} - \Sigma\text{anions} * 100}{\Sigma\text{ions}}$$

Positive reaction errors indicate cation excess and negative reaction errors indicate anion excess. Reaction errors are caused by either errors in determination or the fact that not all possible ions are commonly determined. The cut-off at 2% or 5% is common. Analysis with high errors are omitted in the data processing (Mazor, 1991). The calculated error for the results of the analysis are given in appendix 4 and 5 and range between zero to 2.14% in SP. This is also given in figure 5.2. Therefore the analysis is plausible and the data can be processed.

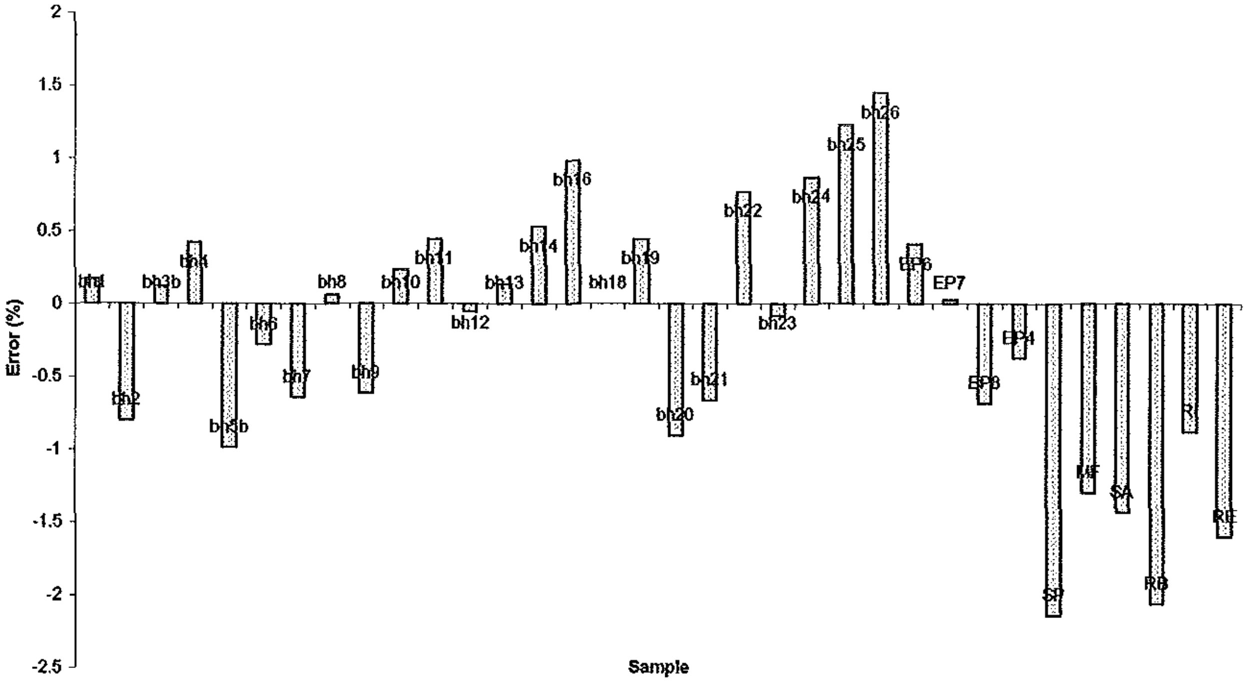


Fig. 5.2: Error(%) for the analysis of groundwater and river water samples

5.3.3 Classification

Hardness is used to classify waters on a scale from very soft to very hard. Calcium and magnesium ions are predominantly connected with hydrogencarbonate ions and to a limited extent with other ions like SO_4, Cl, NO_3, PO_4, etc. The total amount of calcium and magnesium compounds are the total hardness expressed as mg/l $CaCO_3$. Degree of total hardness can be expressed after Hölting 1989 as:

	d°H	meq/l
very soft	0 - 4	0 - 1.43
Soft	4 - 8	1.43 - 2.86
medium hard	8 - 12	2.86 - 4.28
slightly hard	12 - 18	4.28 - 6.42
Hard	18 - 30	6.42 - 10.72
very hard	> 30	> 10.72

Table 5.5: Hardness classification of water

The total hardness of the groundwater as $CaCO_3$ given in table 5.1 ranges from 160 mg/l in bh05b to 248 mg/l in bh12. This is converted to Grad Deutsche Härte (german degree of hardness or d°H) by dividing with 17.86 and it ranges between 8.96 d°H to 13.89 d°H in bh05b and bh12, respectively. The d°H values are converted to a less confusing unit meq/l by dividing with 2.8. The hardness in bh05b to bh12 varies between 3.2 meq/l to 4.96 meq/l which indicates medium hard to slightly hard water. As the hardness of water depends on the concentration of calcium and magnesium, this property of the water can be determined by adding the meq/l concentration of Ca and Mg. Using the meq/l concentration of the analysis given in appendix 5, the hardness of waters in table 5.2 was determined. Boreholes SA an MF show higher hardness of 5.95 meq/l and 6.28 meq/l, respectively. The groundwater in the whole has hardness averaging 4.42 meq/l indicating slightly hard water. The river water has an average hardness of 2.86 meq/l which is between soft to medium hard water. River water and groundwater analysis in SA and MF (Anteneh Girma, 1994) reveal hardnesses of 2.49 meq/l, 3.43 meq/l and 4.64 meq/l, respectively. The increase in the hardness of the waters may be indicative of human impact.

Graphical representation of hydrochemical analysis is an important basis for interpretation and comparison. There are several different diagrams, however the piper diagram is very widely used. This can be utilised for classification and interpretation of water origin. To represent the analysis in a piper diagram the concentration in meq/l of major cations and anions have been converted into percent meq/l appendix 6. These data are plotted in the trilinear diagram (figure 5.3).

The rhomb in piper diagram is subdivided into seven sections, each presenting special water type:

normal alkaline earth freshwater

a - prevailing bicarbonatic

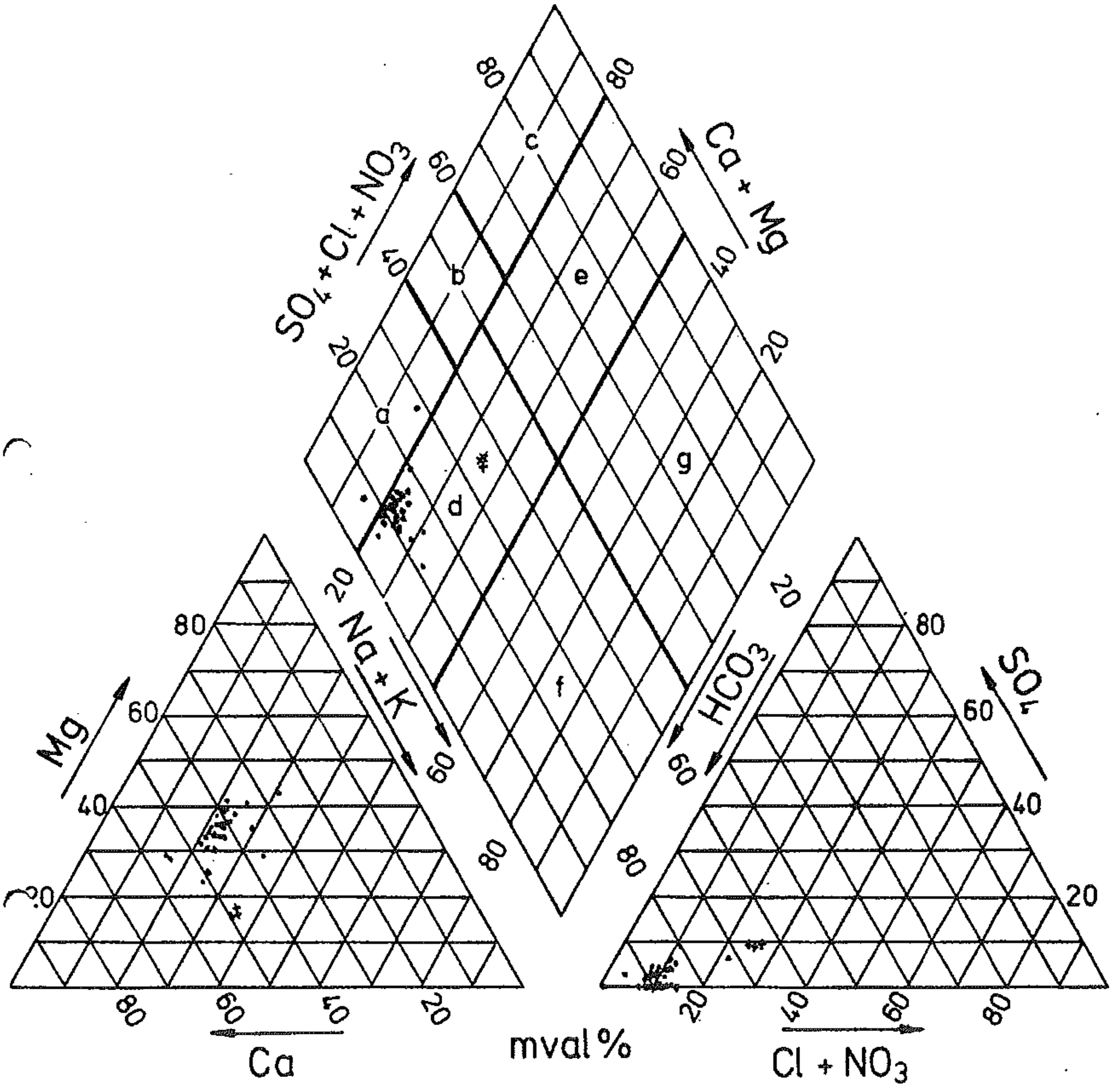
b - bicarbonatic - sulphatic

c - prevailing sulphatic

alkaline earth freshwater with higher contents of alkalies

d - prevailing bicarbonatic

e- prevailing sulphatic



• groundwater, + river water, mval% represent meq/l%

Fig. 5.3: Groundwater and river water type presented in piper diagram

alkaline freshwater

f - prevailing bicarbonatic

g - prevailing sulphatic - chloridic

All the water from the groundwater and the river water plot in section d except bh23 and SA which fall in section a (figure 5.3). These two boreholes show relatively lower alkali metals. Both section d and a indicate alkaline earth prevailing bicarbonate water. Section d shows that the waters have relatively higher alkali metals. Although the river and the ground water plot in the same section in the quadrilateral field, it is apparent in the cation and anion triangles also in the rhomb that the river water has higher concentration of chloride, nitrate, sulphate and lower concentration of magnesium and bicarbonate.

5.3.4 Data interpretation

From the result discussed before, it is apparent that the water is dominated with calcium magnesium and sodium cations and bicarbonate anion. It is saturated with respect to silica. These earth alkali and alkali metals with silica are major constituents of igneous rock minerals

Calcium is an essential constituent of pyroxene, amphibole and plagioclase feldspars. The alkali metals sodium and potassium are important constituents of the feldspars. The feldspars are tectosilicates, with some aluminium substituted for silica and with other cations compensating for the positive charge deficiency that results. The common feldspars are orthoclase and microcline, which can be described by the formula $KAlSi_3O_8$, and the plagioclase series ranging in composition from albite, $NaAlSi_3O_8$, to anorthite, $CaAl_2Si_2O_8$. Potassium feldspar is more resistant to chemical attack. However, species containing sodium and calcium are more susceptible to weathering and they yield the metals Na^+, Ca^{2+} and silica into solution. The decomposition of sodium feldspar, albite, can be represented as:

$$2NaAlSi_3O_8(c) + 2H^+ + 9H_2O(l) \rightarrow Al_2Si_2O_5(OH)_4(c) + 4H_4SiO_4(aq) + 2Na^+$$

Similar decompositions of calcium and potassium feldspars yield the cations Ca^{2+} and K^+. The water that has been in contact with these minerals in the study area is excepted to have calcium, sodium and potassium. Increased concentration of sodium in the river water can be originated from sewage and industrial effluents (chapman, 1996). Human activities contribute also to rising calcium concentrations. This is visible in the higher concentration in SA and MF. In addition to its difficulty to be liberated from silicate mineral structures potassium has strong tendency to be reincorporated into space between crystal layers in certain clay minerals. Hence, the concentration of potassium in the ground water is low. The higher concentration of potassium in the river water may be due to industrial discharges and run off from agricultural land.

Magnesium and iron are major constituents of mafic minerals in igneous rocks. These include the pyroxenes, amphibole, biotite and olivine. The latter is solid solution whose end members are forsterite (Mg_2SiO_4) and fayalite (Fe_2SiO_4). The alteration of this mineral yield Mg^{2+}, Fe^{2+} and silicate ions. The reaction is somewhat similar to that shown for the feldspars. Although magnesium is used in many industrial process it contributes little to water quality alterations (Chapman, 1996). Therefore, the magnesium is derived mainly from the weathering of these feromagnesium minerals. This is evident from the result of the analysis in which most of the groundwater shows similar concentration ranging between 19 mg/l to 29 mg/l except the fresher end members bh05b and bh020 which contain less magnesium. The river water has the lowest concentration which confirms that the magnesium is principally derived from rock-water rock interaction. The magnesium along with calcium is the main contributor to the water hardness in the analysis. Therefore, the groundwater which has higher concentrations of calcium and magnesium (i.e. MF) is the hardest end member and the river with relatively lower concentration is soft.

The Fe^{2+} ion which is released by attack of mafic minerals by water is the most mobile in groundwater. The solubility of iron is a function of oxidation and pH condition. Iron is relatively soluble at lower pH less than 5 under moderate oxidising conditions. Mostly the iron is reprecipitated (Hem, 1992). The present oxidising environment and pH cause the precipitation of ferric hydroxide, $Fe(OH)_3$. Hence, the total concentration of iron in the groundwater is low. However higher concentration of total iron is observed in the river water due to lower pH condition.

Silica which is released by weathering of silicate minerals exists in water generally in the form of H_4SiO_4 (aq) but is usually recorded as silica SiO_2. According to Langmuir, (1997) typical silica concentrations in groundwaters in contact with pyroclastic volcanics can reach up to 85 mg/l (abundant mafic minerals and high rock surface areas) and in fresh basalts up to 50 mg/l (mafic minerals). The analysis of the groundwaters which range between 50 mg/l to 76.5 mg/l vary exactly in this range.

Bicarbonate is the major ion in the groundwater and the river water which determines the TDS. The MF which has the highest TDS contains also higher concentrations of HCO_3 and the river with the lowest TDS displays lower HCO_3 concentration. This is apparent from the compositional diagram HCO_3 versus TDS in figure 5.6, that the mixing line extrapolates to the HCO_3 axis indicating that both intermixing waters contain a significant concentration of HCO_3. This can be confirmed by the compositional diagram of Ca or Mg versus TDS (figure 5.6). The mixing line extrapolates to a point along the TDS axis, indicating that the fresher end member contains significant concentrations of ions other than Ca or Mg. The Bicarbonate ion in this basaltic environment is produced by the reaction of OH^- ions which are released from silicate weathering under presence of free CO_2, which maintains the Ca-CO_2 equilibrium. The CO_2 concentration of the groundwater which is measured in the field averages 27.7 mg/l (table 5.1). The concentrations of CO_2 given in table 5.2 is measured in the laboratory and indicate the bound CO_2. The production of HCO_3 can be represented as (Mathess, 1982):

$$2NaAlSi_3O8 + 11H_2O + 2CO_2 \rightarrow Al_2Si_2O5(OH)_4 + 2Na + 2HCO_3^- + 4H_4SiO_4$$

The chemical weathering of Al-silicates like albite or K-feldspar controls the CO_2 content of the water and therefore its pH (Langmuir, 1997). However, additional formation of HCO_3^- decreases the pH rise associated with feldspar alteration. Since in natural systems CO_2 is almost always present, bicarbonate is produced rather than OH^- (Drever, 1988):

$$OH^- + CO_2 \rightarrow HCO_3^-$$

This ion is responsible for the alkalinity. The groundwater possesses an average bicarbonate alkalinity of 245 mg/l. The bicarbonate ion keeps the water in buffer solution i.e. the pH is controlled by reversible equililbria.

Chloride, fluoride and sulphate are minor constituents in this analysis. Chloride is present in igneous rock minerals like feldspathoid sodolite, and replacing hydroxide in biotite and hornblende and may be in solid solution in glassy rocks. Chloride is also derived from the atmosphere through rain water. On the whole, igneous rocks can not yield very high concentration of chloride to normally circulating groundwater. Therefore the chloride concentration in the groundwater is low ranging between 8 mg/l to 14.2 mg/l. The higher concentration of chloride in borehole bh08, MF, SA and the river water indicate point source pollutions. This pollution can contain industrial or sewage effluents but also agricultural runoff. Because of the conservative nature of chloride, it is often used as a tracer in groundwater.

The increased concentration of chloride due to pollution is accompanied by higher concentrations of nitrate in the same boreholes and river water. Figure 5.4 and 5.5 show the concentration map of chloride and nitrate, respectively.

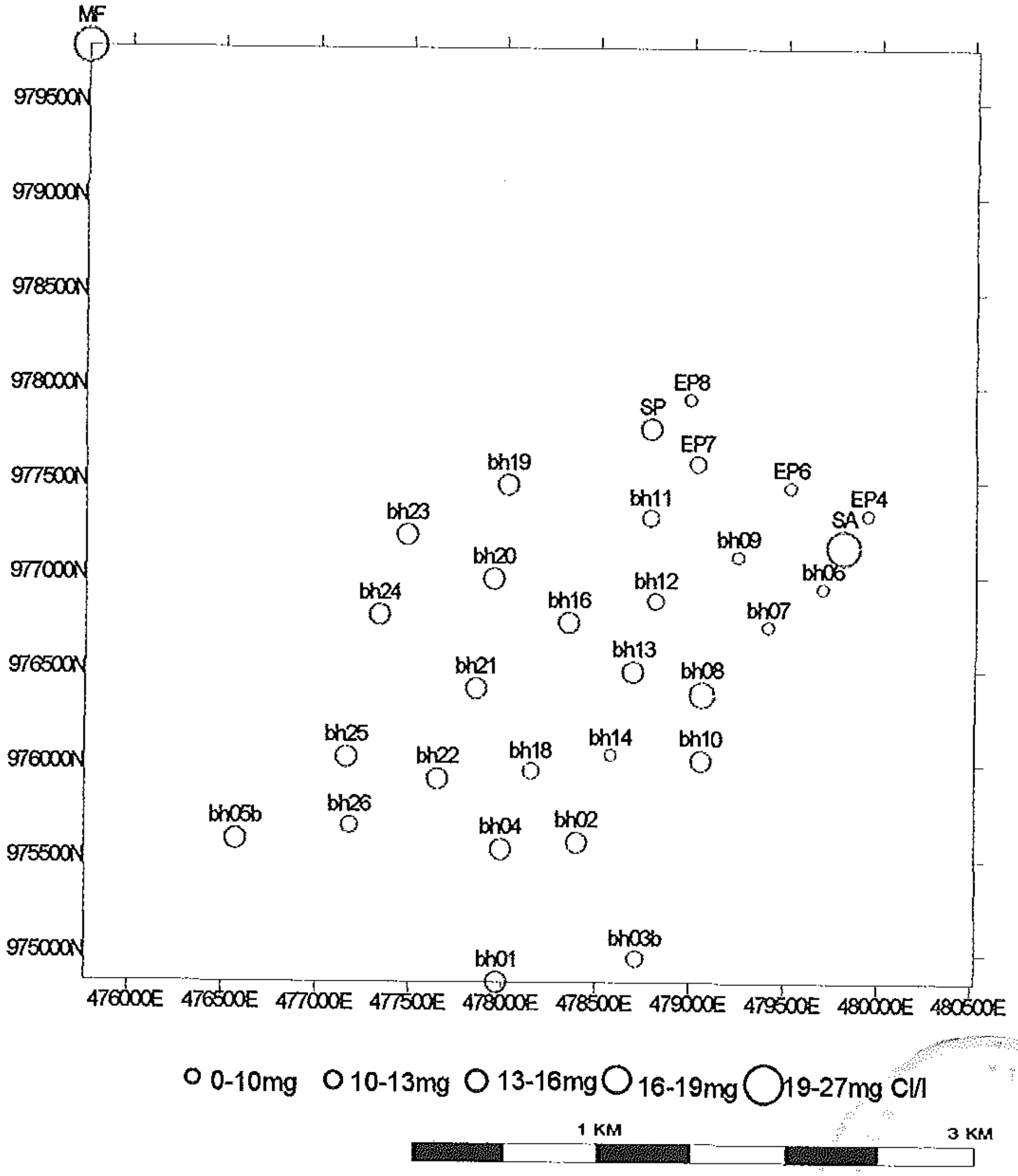


Fig. 5.4: Chloride map of the groundwater plotted as individual values.

Nitrogen is present in the atmosphere as N_2 molecule. Rain water contains dissolved nitrate and ammonia. In soil and groundwater, oxidation and reduction of nitrogen species are accomplished by micro-organisms. Under anaerobic conditions denitrification takes place which releases nitrogen gas as an end product. Under oxidising conditions in groundwater and river water nitrate is prevailing. However, exceptions are seen in bh18 and bh25 which have increased concentration of nitrite. This can be error in measurments. Concentration of nitrate greater than 10 mg/l indicates influence by human activities. SA borehole which is near Sidamo Awash village shows a nitrate amount of 53 mg/l exceeding USEPA limit for drinking water standards (appendix 3).

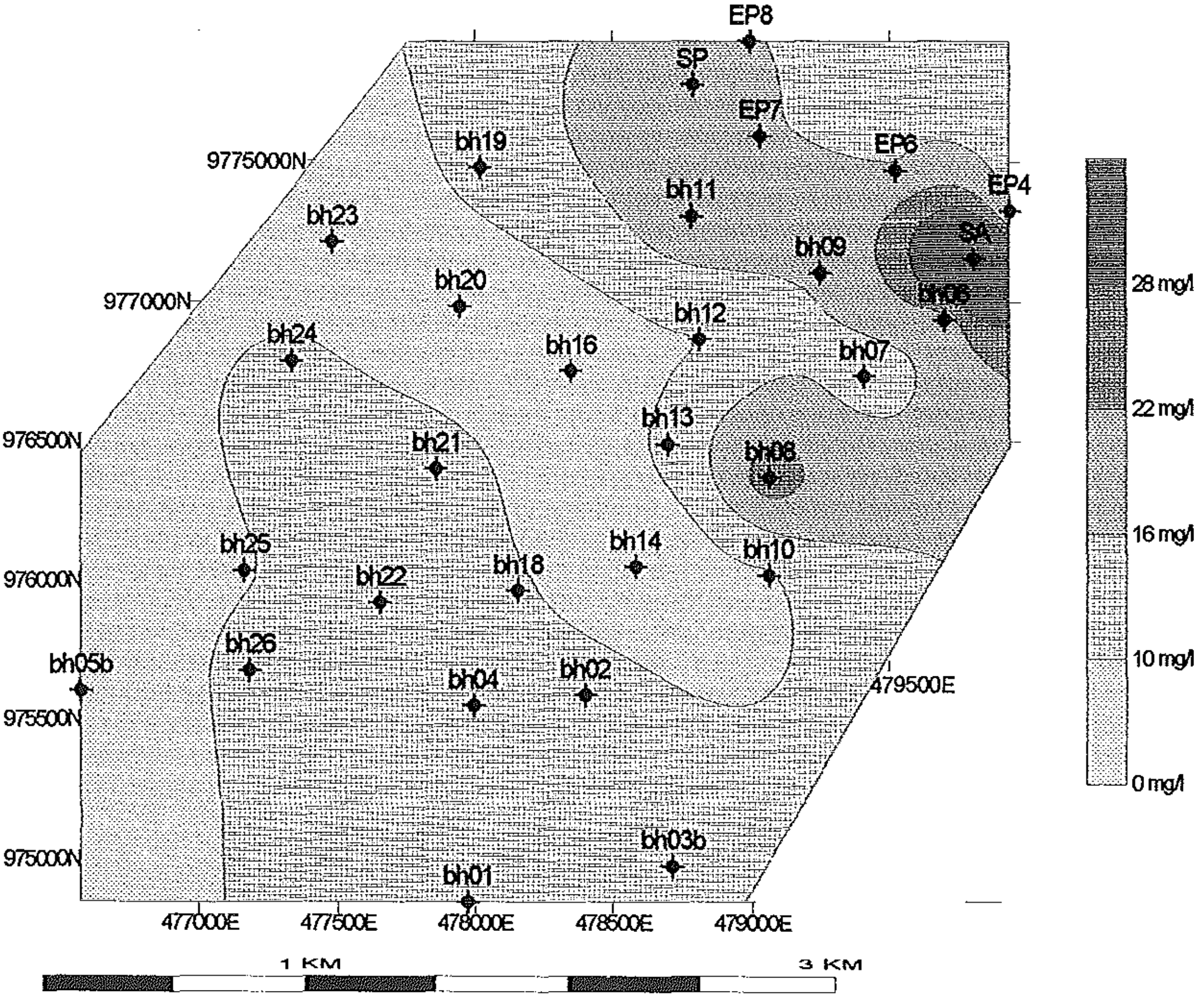


Fig. 5.5: Nitrate distribution map of the groundwater.

Fluoride originates from weathering of fluoride containing minerals like apatite or hornblende in which the hydroxide is replaced by fluoride. Rocks rich in alkali metals are high in fluoride content. The mobility of fluoride in water depends on the Ca^{2+} ion content since fluoride forms low solubility compounds with divalent cations (Chapman, 1996). As the rocks in this area are dominated with divalent cations of the alkali earth metals and iron the fluoride content is low and the solubility of fluoride is also less. Therefore, low concentration of fluoride less than 1 mg/l both in the groundwater and river water are observable. Higher average concentrations of fluoride in the river can be due to effluents from industries like metal factory (Chapman, 1996).

Sulphate is released by weathering of sulphate containing minerals. The sulphate in the groundwater and the river water is mainly derived from rain and decay of micro-organisms. Hence, concentration of sulphate in the groundwater is low averaging 7.2 mg/l. The higher concentration of this ion in some of the boreholes like bh21, SA, MF and the river water can be due to human impact by agriculture and industrial discharge.

Phosphorous occurs in apatite and is released by weathering. Dissolved phosphorus in water is commonly determined as orthophosphate. Phosphate is also released to the environment from mineral fertilisers, animal wastes, sewage and detergents. Dissolved phosphorous is readily absorbed on to clay minerals and metal hydroxides and is also used in the biological cycle (Mathess, 1982). These are reasons for its very low mobility in groundwater. Therefore, the analysis of the groundwater indicated concentrations lower than 0.1 mg/l. Concentrations of phosphate in river water exceeding 1.4 mg/l (Antenrh Girma, 1994) imply pollution by human activities.

From the result displayed in table 5.2 the heavy metals show low concentrations <0.1 mg/l except zinc in boreholes EP4 to EP7 and SA. The increased concentration of zinc in this groundwater is due to the use of this metal for galvanising steel casings and screens to prevent corrosion

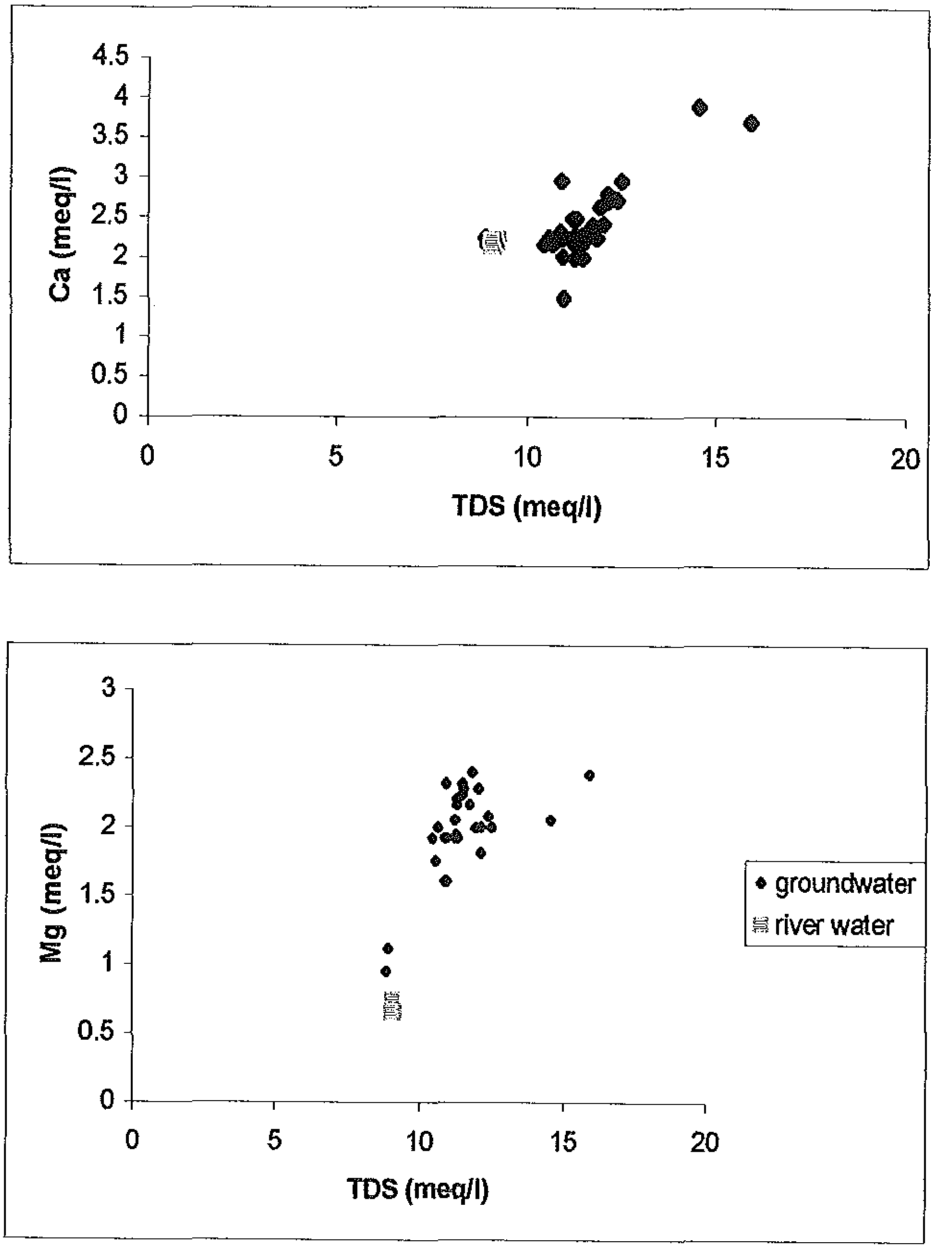
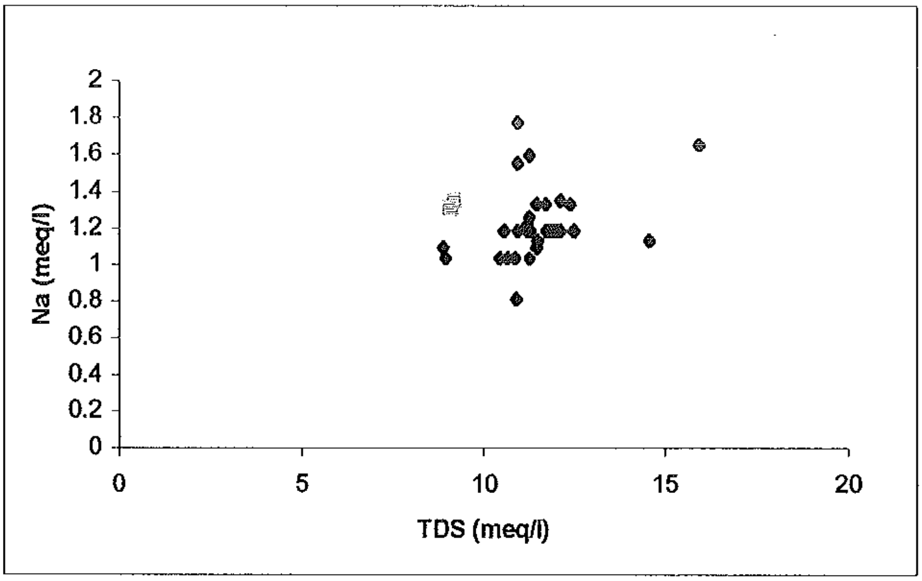
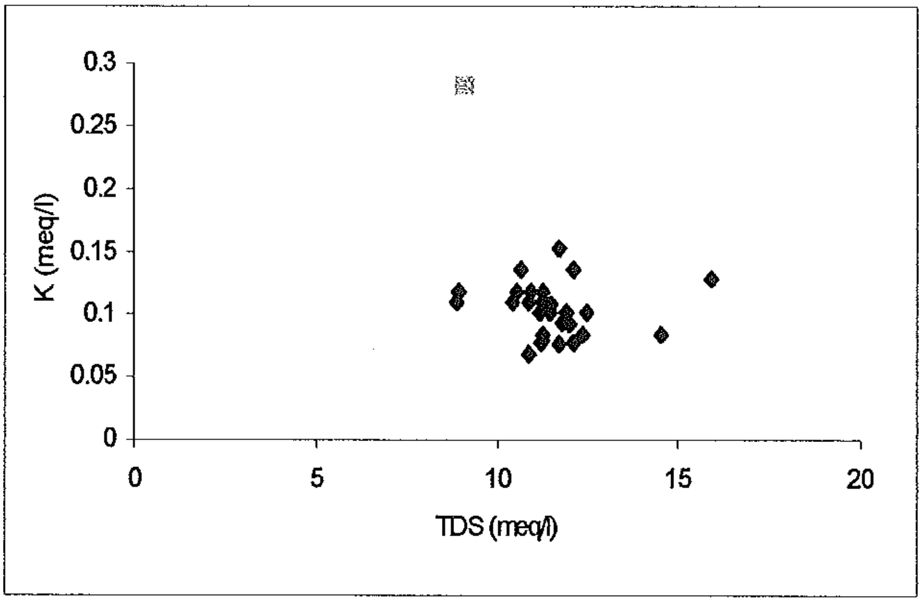


Fig. 5.6: Composition diagram of the groundwater and the river water.





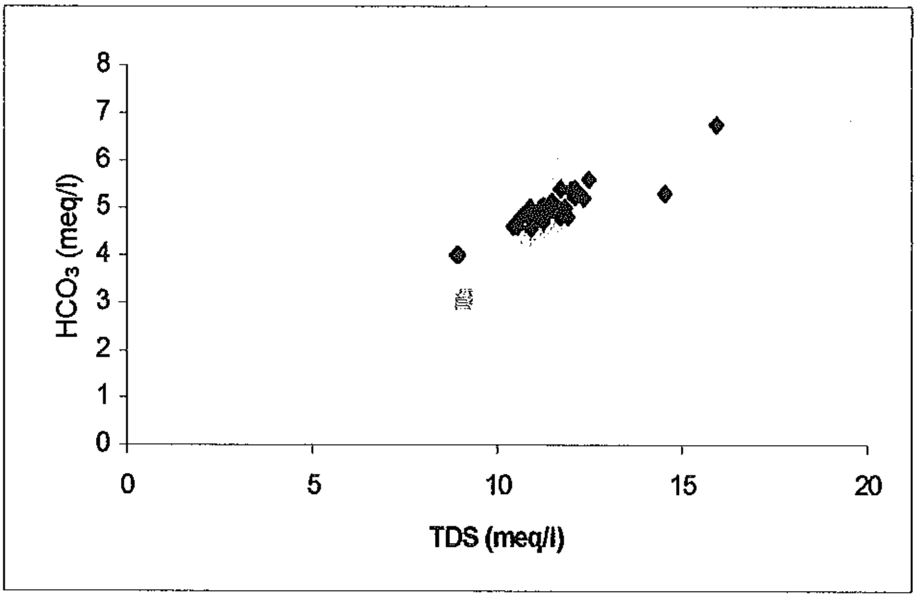
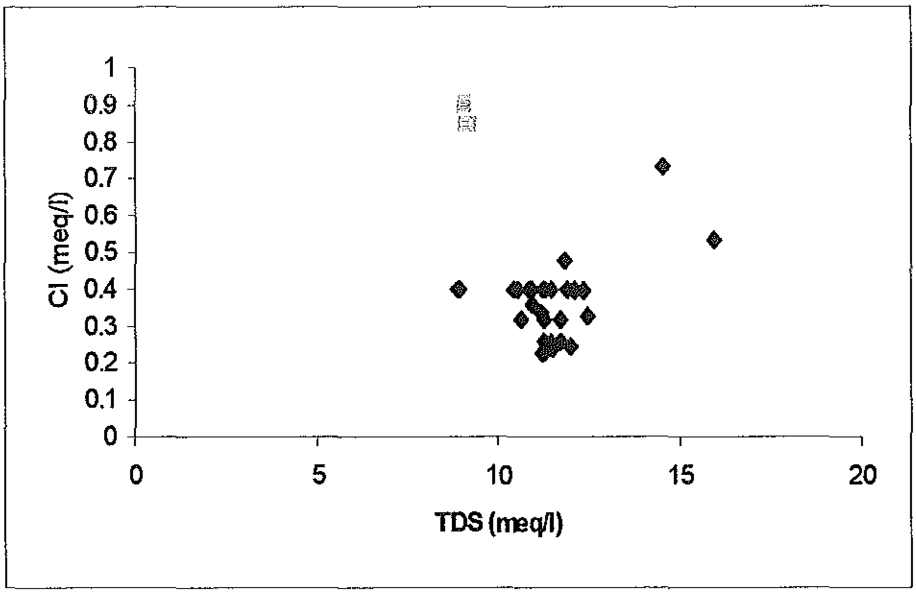
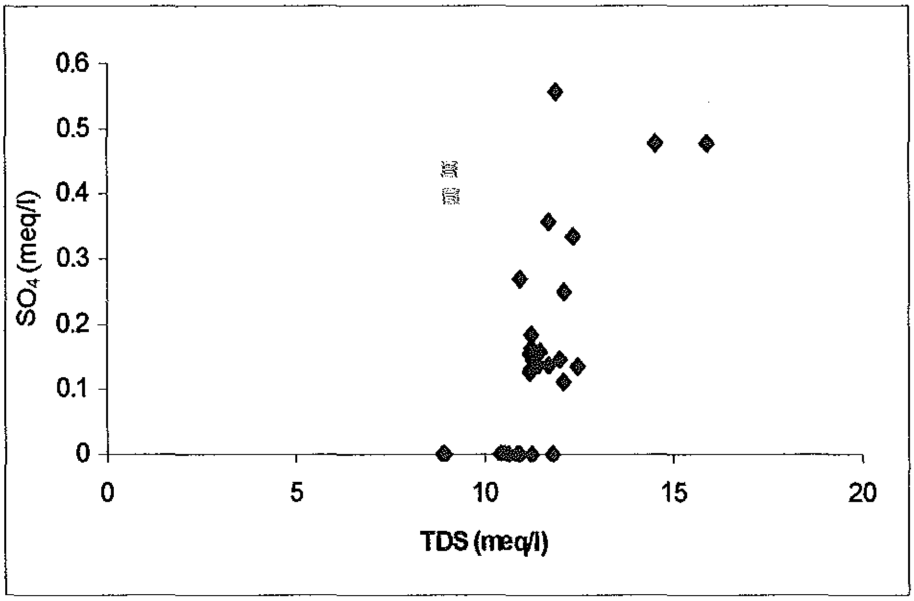


Fig. 5.6: Composition diagram of the groundwater and the river water (cotinued).





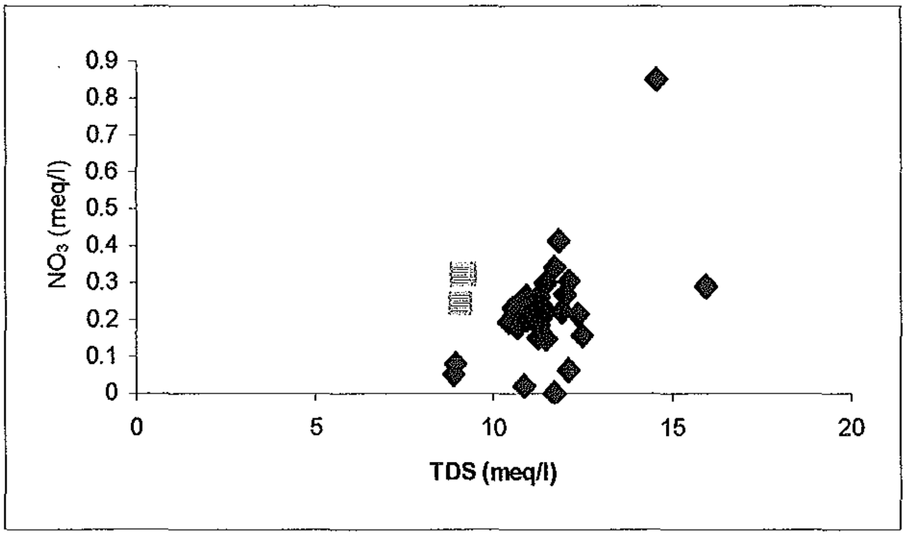


Fig. 5.6: Composition diagram of the groundwater and the river water (continued).

5.4 Stable isotopes

5.4.1 Introduction

Stable environment isotopes are measured as the ratio of the two most abundant isotopes of a given element. Isotopic concentrations are expressed as the difference between the measured ratios of the sample and reference (standard) over the measured ratio of the reference. As fractionation process do not impart huge variation in isotope concentrations, δ-values are expressed in parts per thousand or permil ($^{o}/_{oo}$) difference from the reference. This equation is then expressed as:

$$\delta^{18}O\text{sample} = \frac{(^{18}O/^{16}O)\text{sample} - (^{18}O/^{16}O)\text{reference}}{(^{18}O/^{16}O)\text{reference}} * 1000\ ^{o}/_{oo}\ \text{VSMOW}$$

VSMOW is the name of the reference used, in this case Vienna Standard Mean Oceanic Water. A positive δ-$^{o}/_{oo}$ value signifies that the sample is enriched with ^{18}O relative to the reference. Similarly a sample that is depleted from the reference would have a negative δ-$^{o}/_{oo}$ value (Clark et al., 1997).

Oxygen and hydrogen isotope techniques have been utilised to trace groundwater recharge in the project area. Because of limitation to collect groundwater samples, isotopic analysis have been carried out only for six wells. Oxygen ($^{18}O/^{16}O$) and hydrogen ($^{2}H/^{1}H$) isotope ratios for the groundwater and river water which are calculated with reference to VSMOW are presented in table 5.2. Isotopic composition of rain water for Addis Ababa have been collected at IAEA website WWW.iaea.or.at:80/programs/ri/gnipmain.htm is given in appendix 7.

5.4.2 Meteoric water line

To use ^{18}O and ^{2}H to trace groundwater recharge, it is necessary to know their concentration in the precipitation. The composition of precipitation is reflected, directly or modified, in the composition of the groundwater. The groundwater data is plotted on $\delta^{2}H$-$\delta^{18}O$ diagrams along with the meteoric water line of precipitation as a reference line. The meteoric water line of Addis Ababa has been drawn using the data of the rain water isotopic composition from 1990-1995 (figure 5.7). This results in the equation: $\delta^{2}H = 7.5\delta^{18}O + 12.4$ which is very similar to that defined by Dansgaard (1964) for the northern continental hemisphere meteoric water line

i.e. $\delta^{2}H = (8.1 \pm 1)\,\delta^{18}O + (11 \pm 1)$.

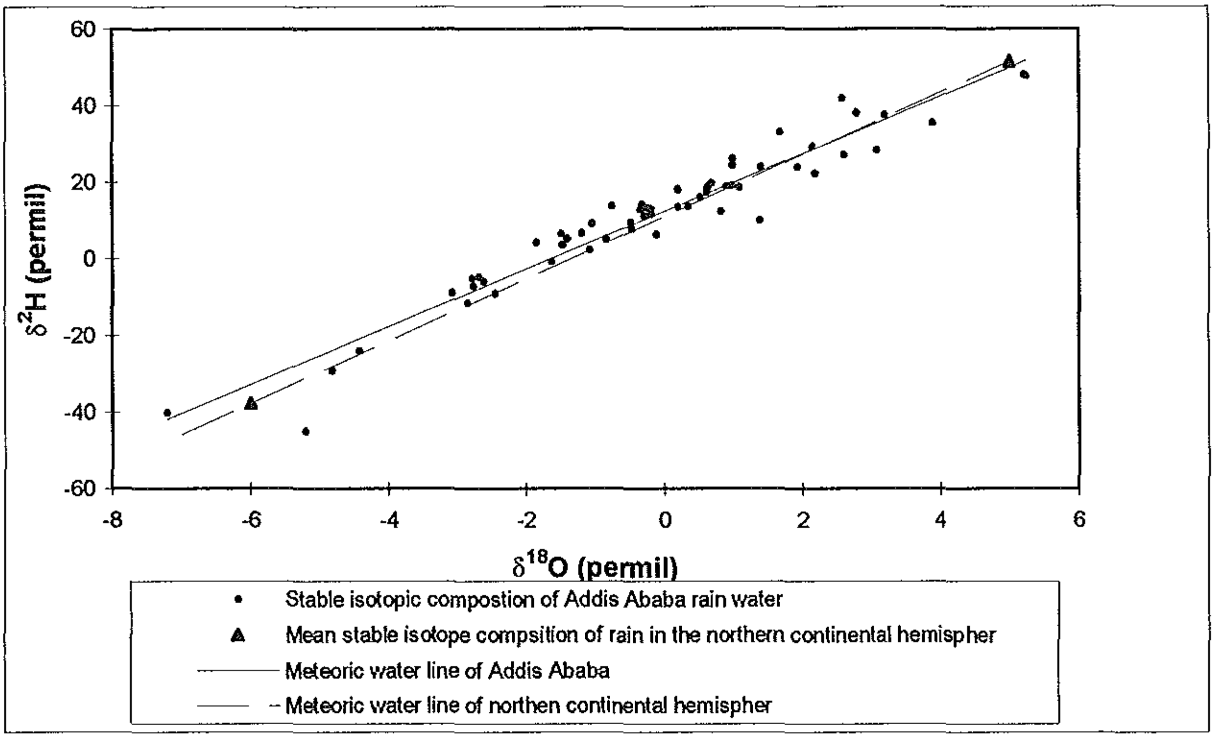


Fig. 5.7: Meteoric water line and $\delta^{2}H$ and $\delta^{18}O$ of Addis Ababa and the northern continental hemispher.

The position of meteoric waters is controlled by a series of temperature based factors. These include vapour mass trajectories over the continents, altitude effect, latitude, seasonal effects and the amount of rain. Hence, in each hydrochemical investigation the local meteoric line has to be established.

The project area receives similar amount of rainfall like Addis Ababa. Latitude and continental effects are negligible. However, the significant variation in altitude can not be neglected. In any region with even minor relief, precipitation will occur as a vapour mass rises over the landscape and cools by expansion, thus driving rain out. At higher altitude regions becoming lighter in isotopic composition. For ^{18}O the depletion varies between about -0.15 and $-0.5^{\circ}/_{oo}$ per 100 m rise in altitude, with a corresponding decrease of approximately -1 to -$4^{\circ}/_{oo}$ for ^{2}H (Clark et. al., 1997). The correction has been determined for the difference in altitude. Change in δ^{18}O is estimated as $0.2^{\circ}/_{oo}$ (i.e. increase) for every 100 m of descent. This compares favourably with values obtained elsewhere; i.e. 0.15 for Cameroon in which the temperature gradient is not very steep and 0.29 for the Kenya Rift Valley. A variation of $1.4^{\circ}/_{oo}$ per 100 m is estimated for δ^{2}H. The project area is around 300 m lower in altitude than Addis Ababa. Therefore correction factors of 0.6 and 4.2 has been applied on the values for δ^{18}O and δ^{2}H, respectively (appendix 8). The local meteoric water line of Akaki has been established using the corrected values (figure 5.8), leading to $\delta^{2}H = 7.5\delta^{18}O + 12.1$. Results show the same slope with Addis Ababa meteoric water line, but a difference in the intercept indicating the variation in altitude.

5.4.3 Groundwater and river water

The stable isotope value for the groundwater ranges between $-5.5^{\circ}/_{oo}$ in EP7 to $0.15^{\circ}/_{oo}$ in SA δ^{2}H and averaging $-3.18^{\circ}/_{oo}$ δ^{2}H, and $-1.9^{\circ}/_{oo}$ in SP to $-1.025^{\circ}/_{oo}$ in SA δ^{18}O and averaging -$1.52^{\circ}/_{oo}$ δ^{18}O. The river water has typical value of $3.57^{\circ}/_{oo}$ δ^{2}H, $-0.68^{\circ}/_{oo}$ δ^{18}O. The local meteoric water appears to range from $-35.9^{\circ}/_{oo}$ in August to $52.3^{\circ}/_{oo}$ δ^{2}H in March. The corresponding $\delta^{18}O$ range is $-6.6^{0}/_{00}$ to $5.83^{0}/_{00}$. The groundwater and the river water data are plotted together with local meteoric water line in figure 5.8.

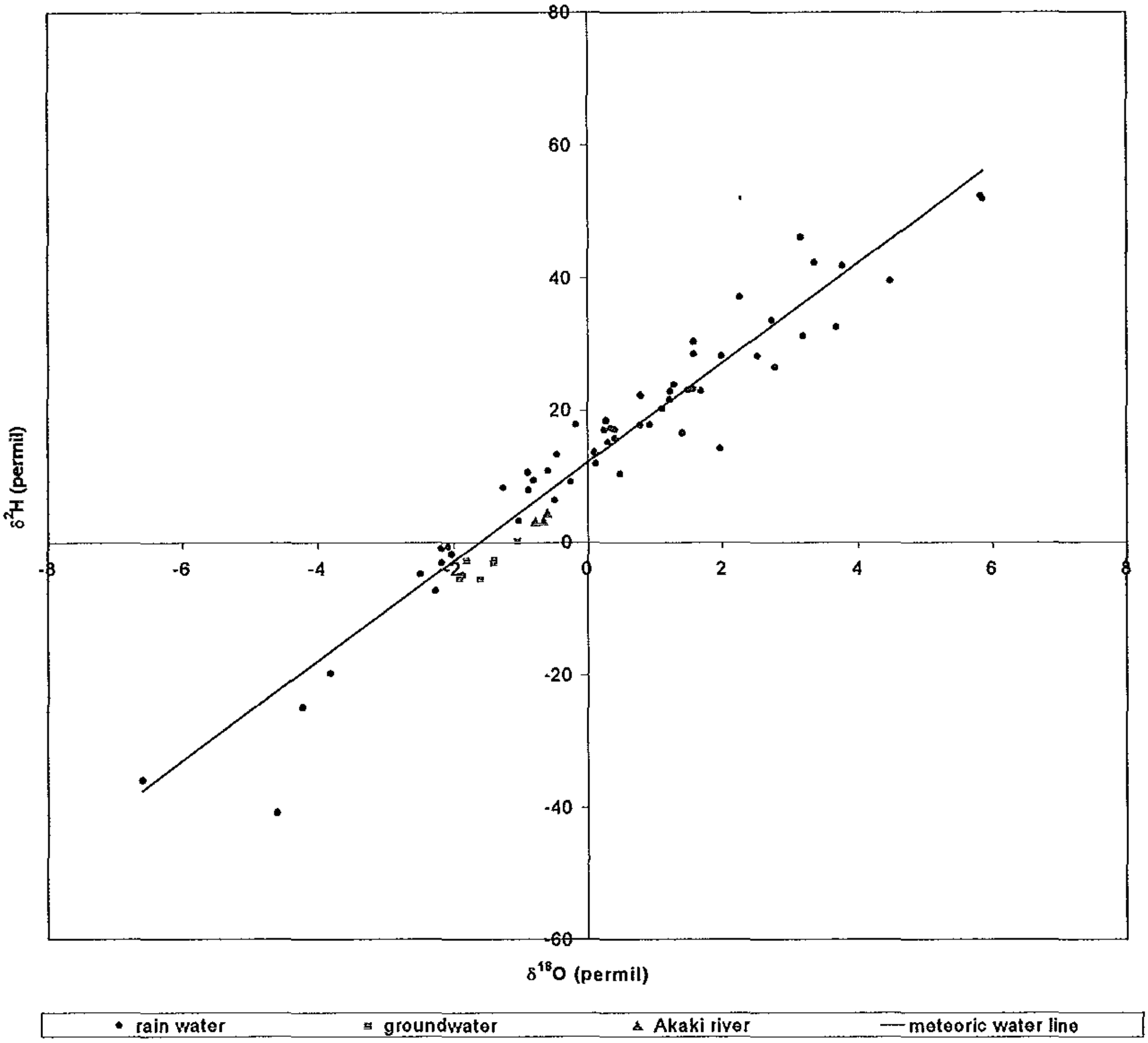


Fig. 5.8: Isotopic composition of the groundwaters and river water plotted along with the local meteoric water line of Akaki.

Results of isotopic composition depicted in figure 5.8 show that the groundwater is lighter than the average rain composition. This can be explained in this way, that only intensive i.e. August and sometimes July rains are effectively recharging the groundwater. As the rainy season in this region starts in June after long dry months, the falling rain drops undergo evaporation, enriching the falling rain with the heavy isotopes. Therefore, the June rain has positive values of δ^2H and $\delta^{18}O$. This effect is less sever in July and August when ambient temperatures are low and the amount of rain is large (as the air gets more saturated). Hence, the precipitation in these months have negative δ^2H and $\delta^{18}O$ values. Since the June rain is generally falling on a dry landscape most of the rain is evaporated. Only a small amount will moisten the upper part of the soil. In July and August after the soil is moistened the water can infiltrate and replenish the field capacity of the soil. After the soil is saturated, macropores and preferential channels in the soil zone permit the fast percolation of water into the unconfined aquifer. Through the fractures in the underlying semi-confined unit this water can proceed to the deeper groundwater. In this rainy season the river water level increases and influent conditions may occur. Therefore, the river water which is enriched with heavy isotopes will mix with the direct infiltrating rain water in the unconfined zone. This mixing between the river water and the direct infiltrating rain water is visible in Figure 5.8 in which the linear data arrays of the groundwater connecting the two end members i.e. the intensive rain events and the river water. Although mixing can be assumed as discussed above, an identical isotope signature could also be produced by the rain water which undergoes secondary process prior to recharge. These processes may be evaporation at the surface or in the unsaturated zone during infiltration. another probability is anthropogenic mixing at the surface. This may be seen in the enriched isotopic composition of SA borehole which is highly influenced by human activities.

5.5 Conclusions

Based on USEPA drinking-water standards and health goals as of September 1998 (appendix 3) most of the well waters are chemically good for drinking water except the groundwater in SA which has nitrate concentration 53 mg/l. Excessive concentration of nitrate cause methemoglobinemia in small children. In contrary to the groundwater, the Akaki river which is rather contaminated by urban wastes, industrial discharge and agricultural run off throughout its course is highly turbid and has large number of total coliforms. The turbidity provide medium for microbial growth and the presence of the total coliforms indicate gastroentric pathogens. Microbes in the water cause diarrhea, cramps, nausea, headaches, or other symptoms. In addition to these, other inorganic contaminants like chromium near Addis Tannery cause adverse effect on health. Therefore Akaki river is not suitable for domestic use.

Considering chemical data plotted in the compositional diagrams Figure 5.6, particularly major ions Mg and HCO_3 reveal mixing of the slightly hard groundwater with softer river water. The Ca diagram also shows a mixing line, however the concentration of this ion is affected by human activities. The river water has already increased Ca concentrations. Alkali metals Na and K which are affected by pollution do not show mixing effects. The minor ions in the analysis Cl, NO_3, and SO_4 show higher concentration in the river due to pollution. The compositional diagram of these ions do not support the mixing theory. However, stable isotope evidence (Section 5.4) tends to hold up the mixing of the ground water and the river water.

Chapter Six

Conclusions and Recommendations

The study area, located in the escarpment of the Main Ethiopian Rift (MER) has climatic condition anticipated in the area with rainfall concentrated in the summer season from June to September. The mean annual rainfall estimated using Thiessen polygons is 1113 mm with a corresponding potential evapotranspiration of 1276 mm (Penman method). The flow in the Akaki river is high during the peak rainy season (June-September) and influent condition may be expected during this time. A preliminary estimate of groundwater recharge using the soil moisture budgeting method suggests around 137 mm annually.

The geology of the area is characterized by volcanics of Late Pliocene and Plio-Pleistocene age of lower basalt flows and young basaltic scoria and lava which belong to the Bofa Basalts and the Bishoftu Basalts, respectively. The lower basalt flows comprise intercalations of basalt flow, scoria, scoracious basalt and tuff. The young basaltic scoria and lava are commonly spatter cones consisting of scoria, scoracious basalt at the top of the cones, surge deposit and volcanic breccia at the bottom of the cone. Alluvial sediments are localized along the Akaki river.

On regional scale the area exhibits the hydrogeological features expected of Upper Awash Basin with the groundwater movement sub-parallel to the general topography. Groundwater flows from all directions to the Akaki river valley. Because of limitations of the water level data, it was not possible to depict the local groundwater flow directions. The permeability of the volcanic rocks in this area is generally high, although there are considerable local variations in transmissivity. The lower basalt flows are the main aquifer in the area. Aquifers are normally found in scoria, fractured or reworked basalts and scoracious basalt but also along the weathered contacts between different lithologic units. The apparent resistivity values in the aquifers range from 50 to 300 Ωm. From the wells drilled in Akaki Well Field D the transmissivity and storage coefficient have been estimated using AQTSOLVE computer program. The transmissivity values in the lower basalts range from 389 to 21600 m^2/day. The storativity values ranging from $2.4*10^{-4}$ to 0.1. The aquifer in the lower basalts is assumed to be semi-confined. The young basaltic scoria reveals high porosity and permeability and represents a good recharge area for the underlying lower basalt. The alluvial sediment is also a local unconfined aquifer with intergranular permeability.

Chemical and stable isotopic data obtained during the present study made it possible to obtain information about the origin of the water, to classify the water type and to determine the mixing pattern of the groundwater and the river water. The chemical composition of the groundwater is distinctive of basaltic terrains with Ca-Mg bicarbonate type water saturated with silica and relatively low TDS values averaging 444 mg/l. The river water influenced by a similar geologic environment has therefore an analogous water type with 389 mg/l average TDS. The highly fractured aquifer pose a possibility for fast pollutant transport. Hence, areas affected by human activities have groundwaters characterized by increased concentrations of nitrate, chloride and sulfate. The Akaki river which is highly polluted by sewage waste, industrial discharge and agricultural runoff has in addition to these pollutants, also higher concentrations of potassium, phosphate, total coliforms and heavy metals like chromium. Based on USEPA drinking water standard the groundwaters have good drinking water quality except the borehole in Sidamo Awash village (SA) which has nitrate concentration of 53 mg/l. In contrary to this, the river water is not at all safe for drinking. The compositional diagrams of the ions, magnesium and bicarbonate indicate the mixing of the groundwater and the river water.

Stable isotopic composition of rainfall data obtained for Addis Ababa from IAEA Vienna have been corrected for altitude difference to construct the local meteoric water line for the area. The stable isotopic composition determined for the groundwater and the river water which is plotted together with the local meteoric water line supports the mixing interpretation.

It is recommended that, to determine the local flow direction, a careful measurement of the static water level in the same time is needed. Even though the regional groundwater flow direction is expected to be to the direction of the river, reversed flow, i.e., from the river to the groundwater system can occur due to reversal of the hydraulic gradient in the course of abstraction from the wells. Therefore, to suggest the highest possible discharge from the wells without causing the influence of the river modeling of the Akaki Well Field D is needed. Precautionary measures like delimitation of water protection zones around the wells also including the recharge area must be carried out to protect the groundwater from contamination. For the delimitation of the water protection zone, in addition to, detailed geological, hydrogeological and hydrochemical investigations future discharge rate (safe yield) must be taken into consideration. The determination of an average flow velocity (application of tracer test) of the groundwater and the properties of the covering layers are the most important criteria for the assessment of protection sectors.

Although mixing can be assumed from the chemical and isotopic analysis and evaluation of the groundwater and the river water, detailed investigations have to be carried out to get firm conclusions. Multisampling for stable isotopic determination of the groundwater, the river water and the rain water is necessary to acquire enough data for the calculation of average values to gain an insight into the investigated system in the lateral, vertical and time dimensions. It is also important to carry out a comprehensive surface water quality study and to increase environmental awareness on the pollutants.

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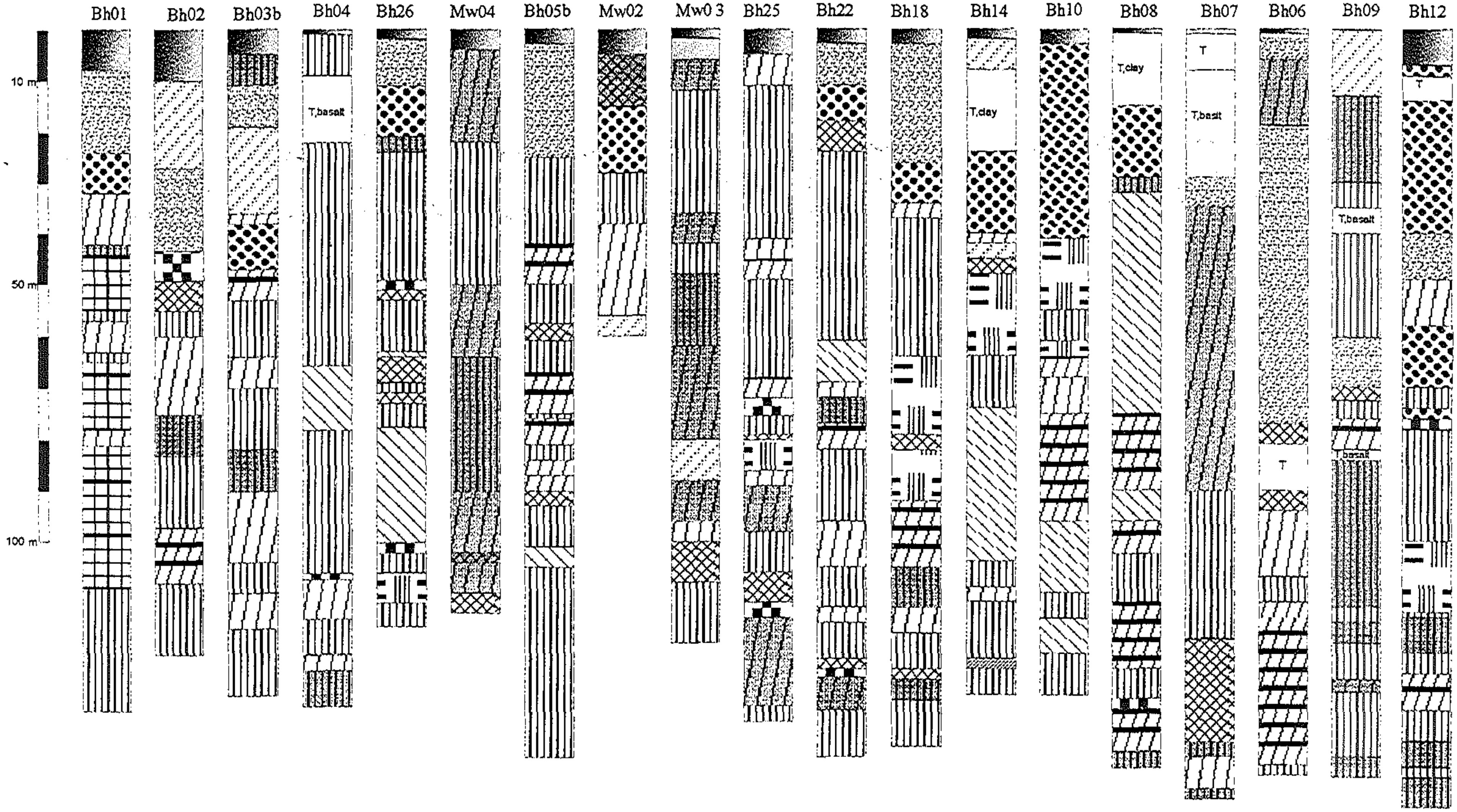
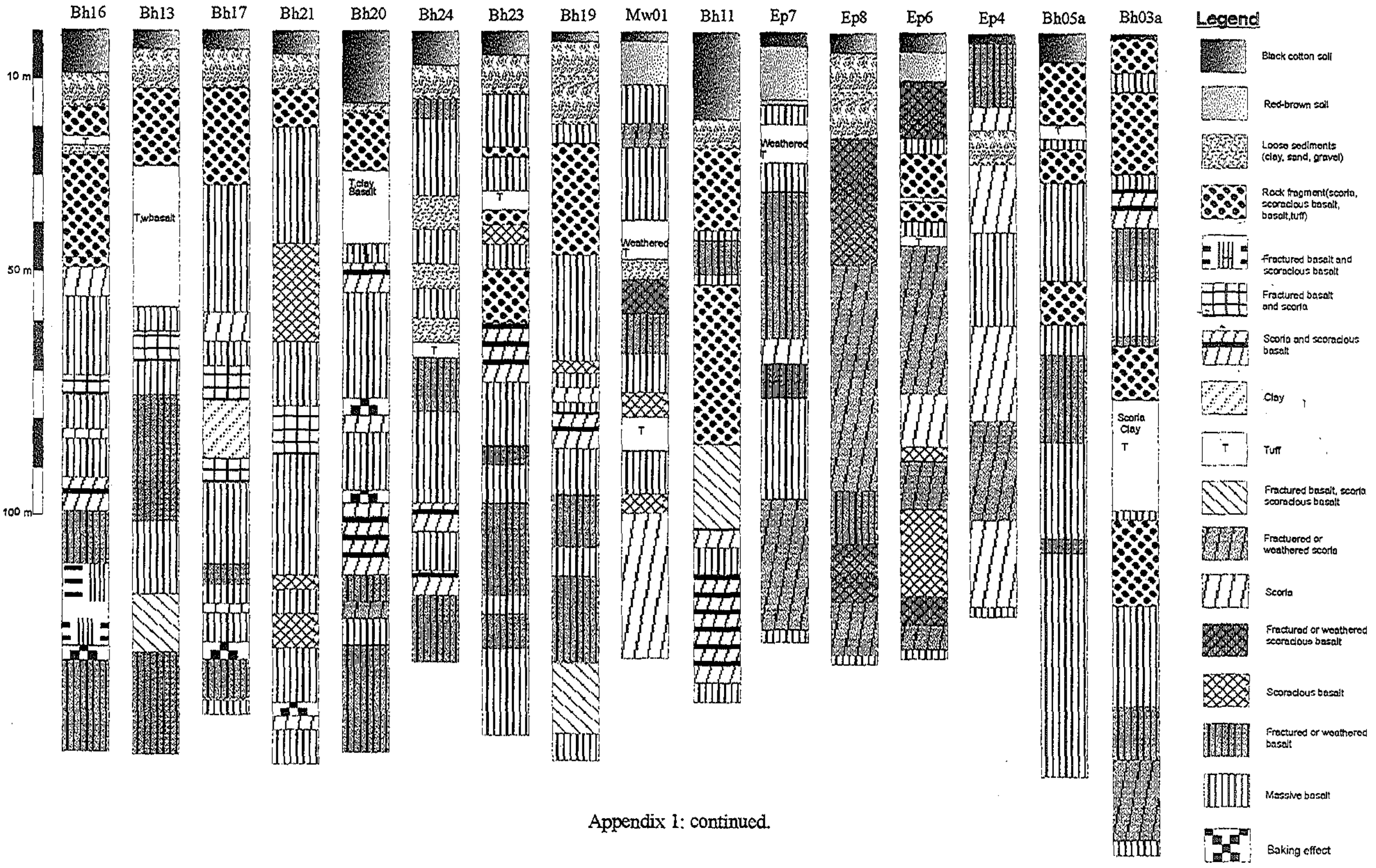
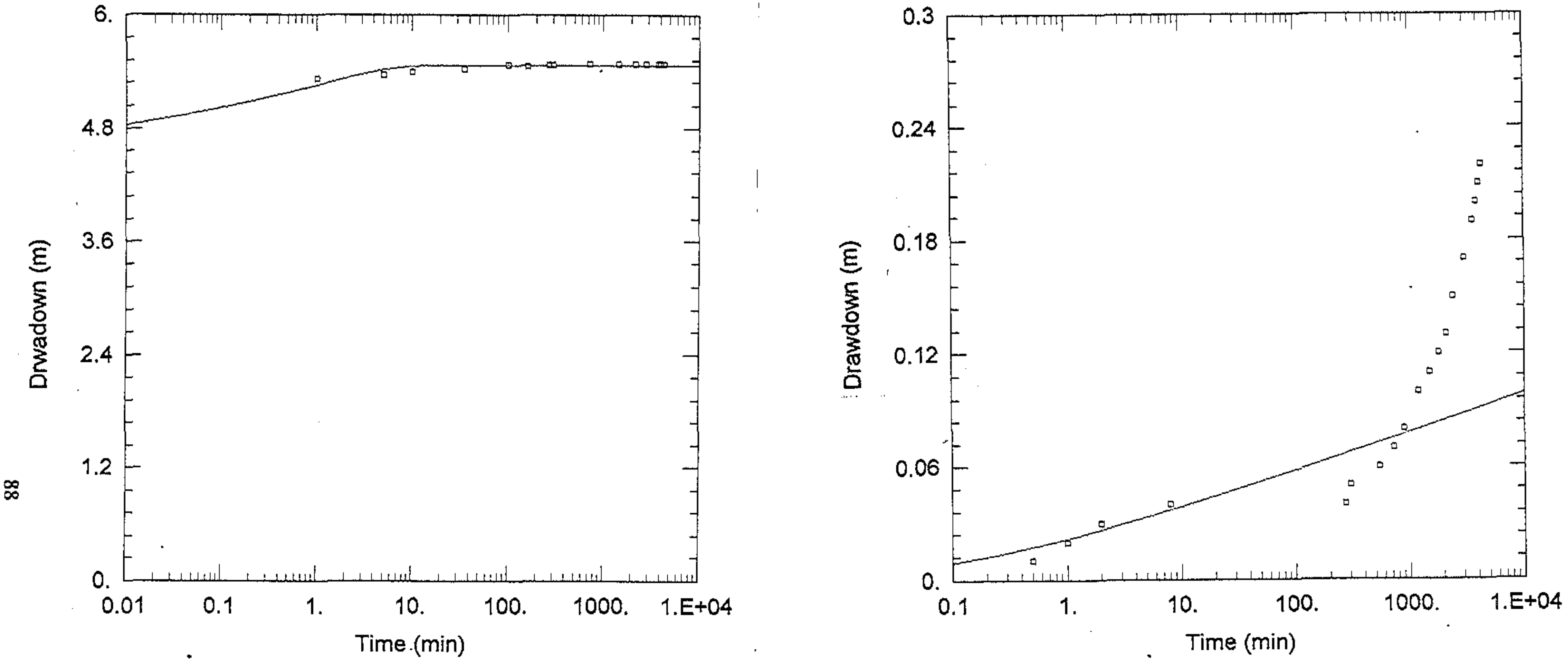


Appendix 1: Well logs in Akaki Well Field D. Location of the wells is shown in figure 4.3.



Appendix 1: continued.



Well: bh01

Solution: Moench

T = 2120 m^2/day

S = 0.00061

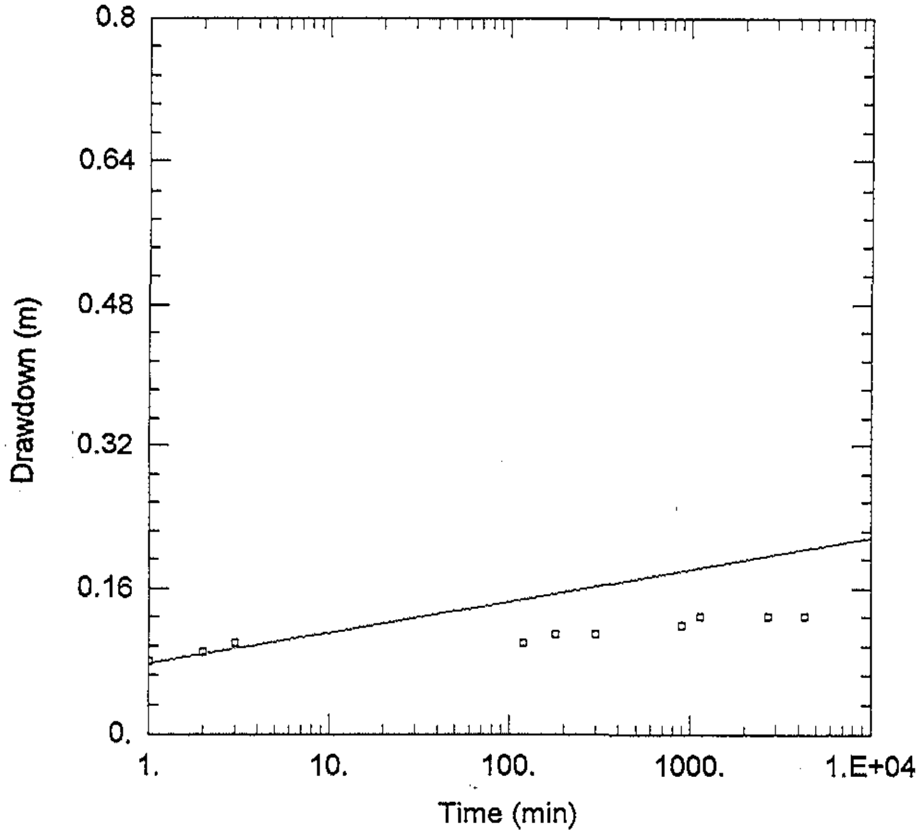
Well: EP4

Solution: Hantush

T = 6532 m^2/day

S = 0.042

Appendix 2: Time-drawdown curves and transmissivity and storativity values in Akaki Well Field D.

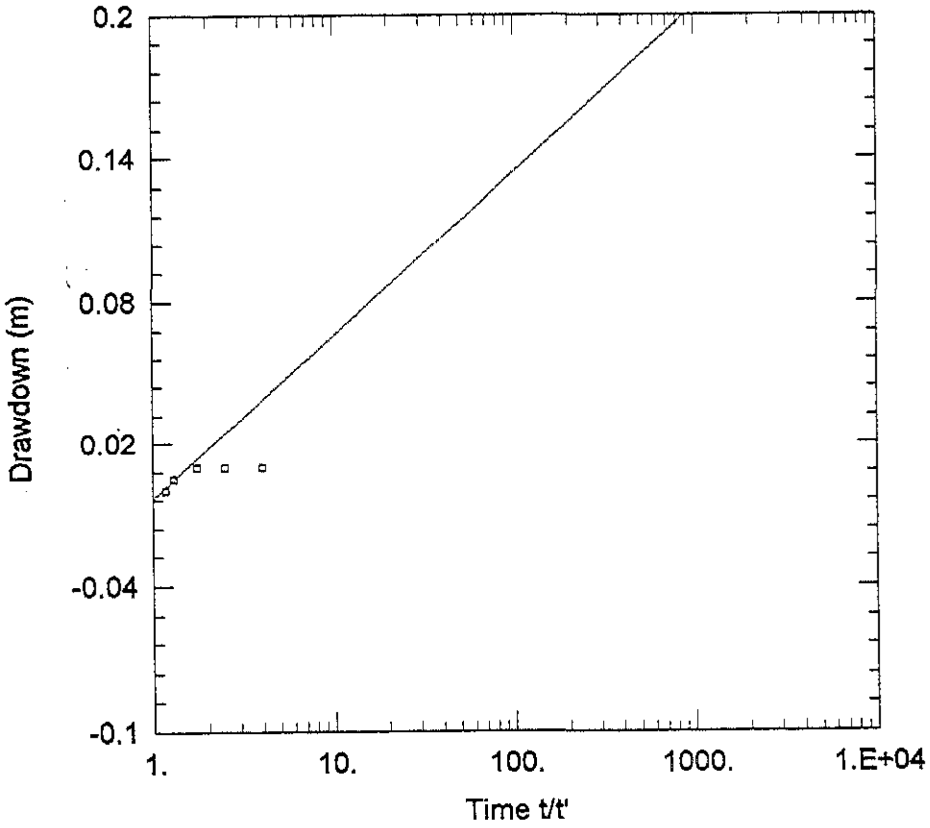


Well: bh06

Solution: Hantush

T = 19454 m^2/day

S = 0.004

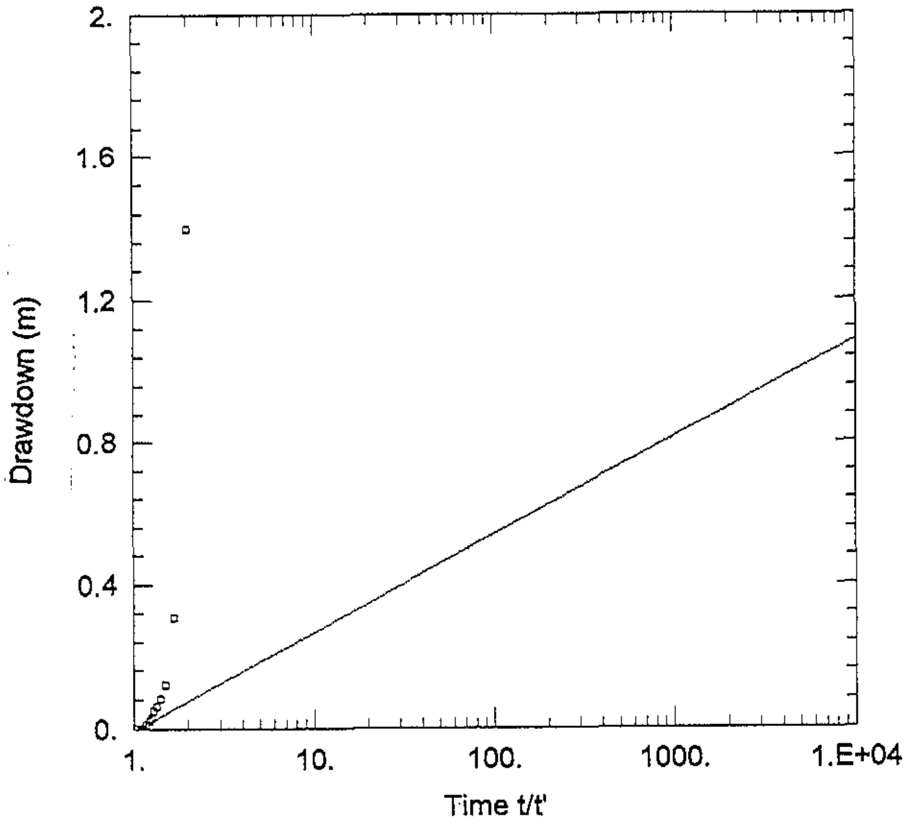


Well: bh06

Solution: Theis recovery

T = 20146 m^2/day

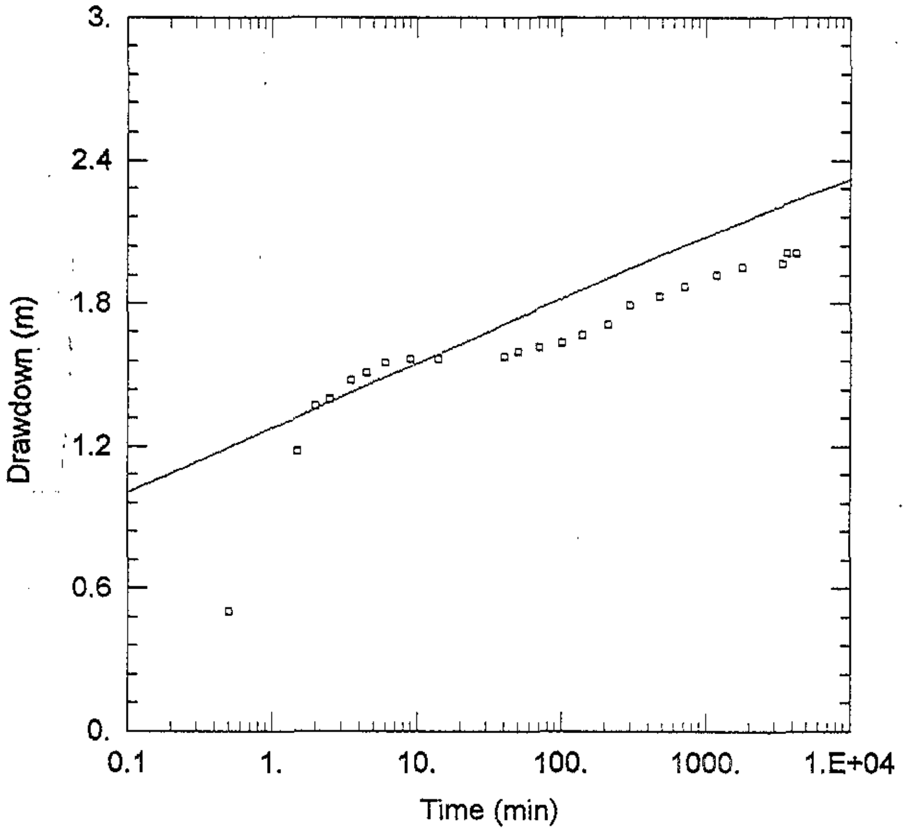
Appendix 2: continued



Well: EP7

Solution: Theis recovery

T = 1908 m^2/day



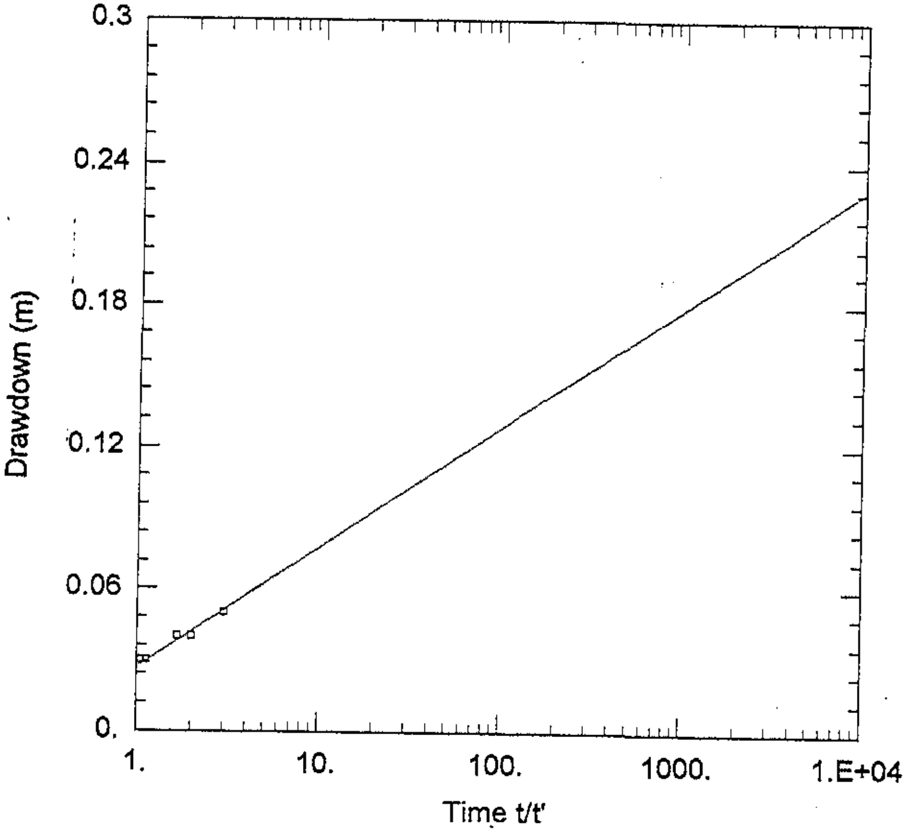
Well: EP7

Solution: Hantush

T = 1909m^2/day

S = 0.0014

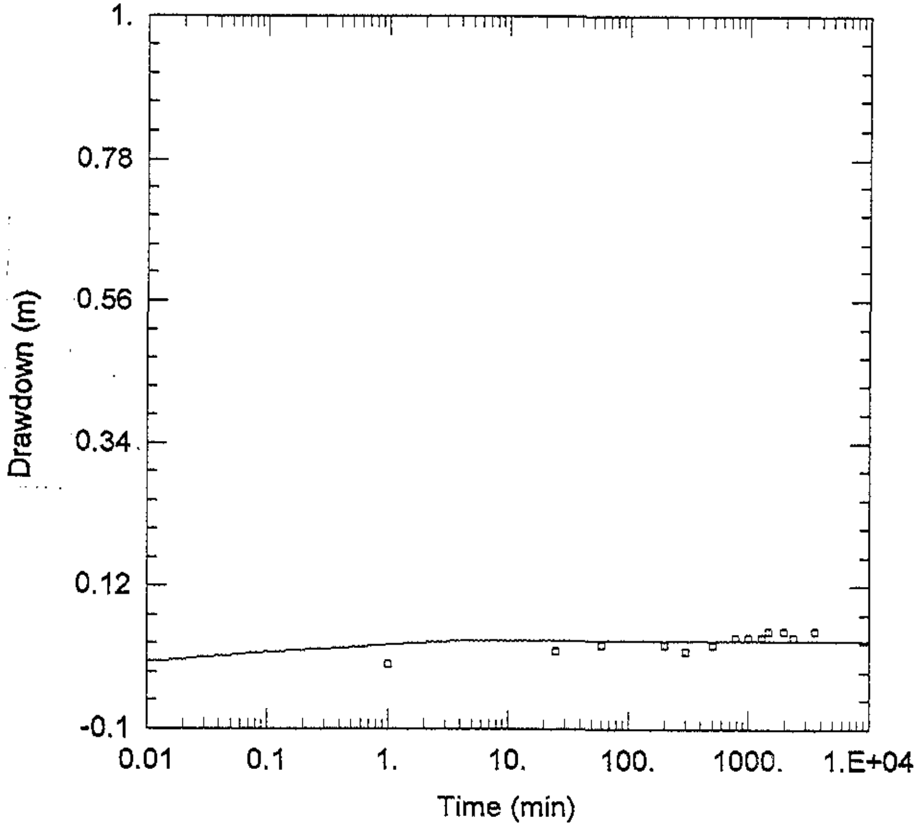
Appendix 2: continued



Well: bh07

Solution: Theis recovery

T = 21614 m^2/day



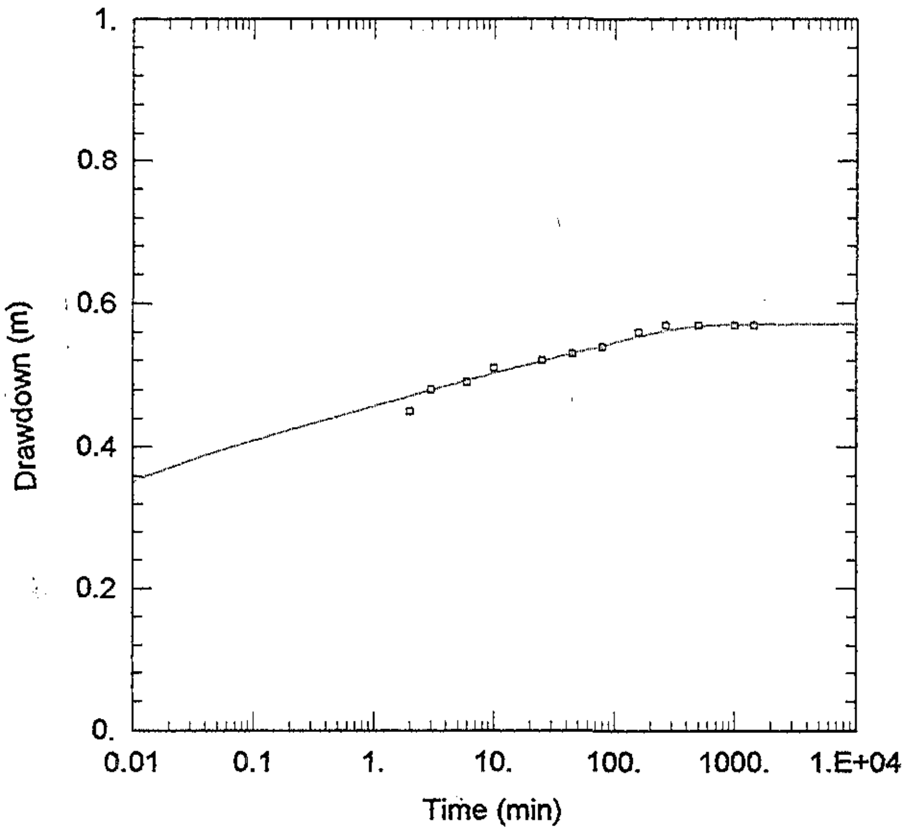
Well: bh08

Solution: Moench

T = 21600 m^2/day

S = 0.0632

Appendix 2: continued.

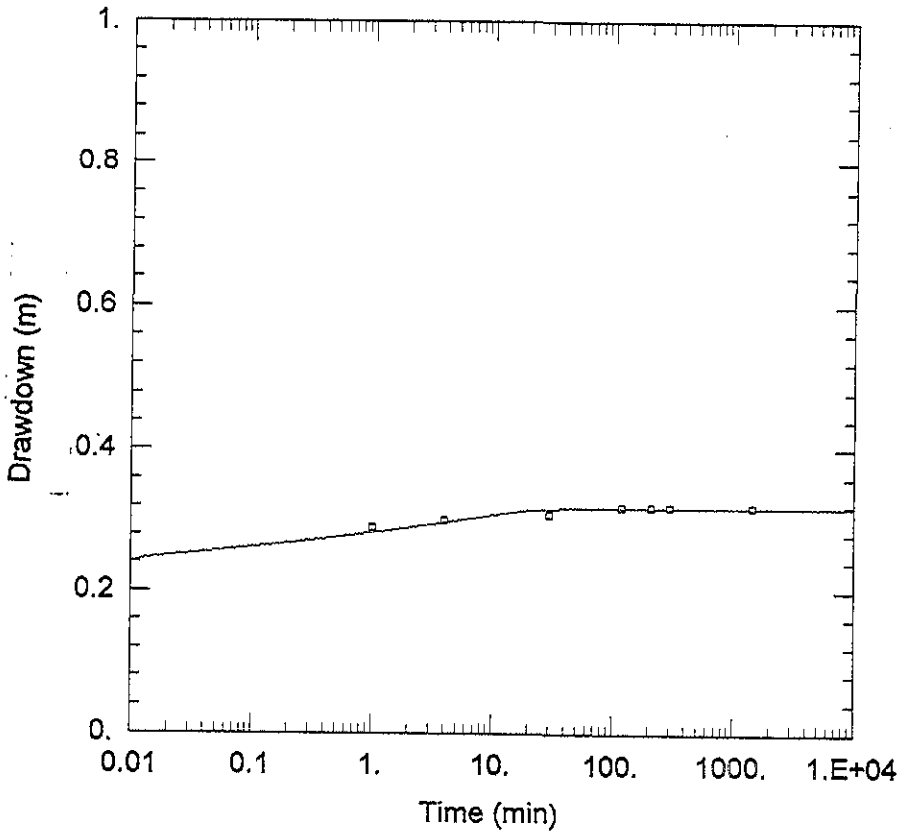


Well: bh12

Solution: Moench

T = 14875 m^2/day

S = 0.000438



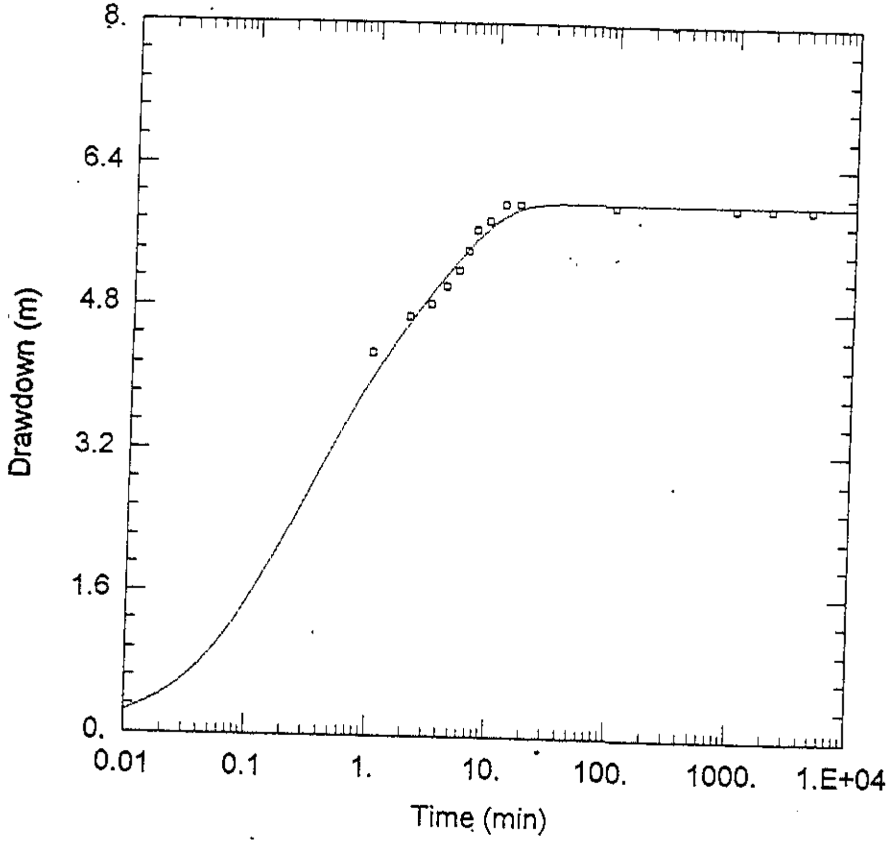
Well: bh14

Solution: Moench

T = 13162 m^2/day

S = 0.056

Appendix 2: continued

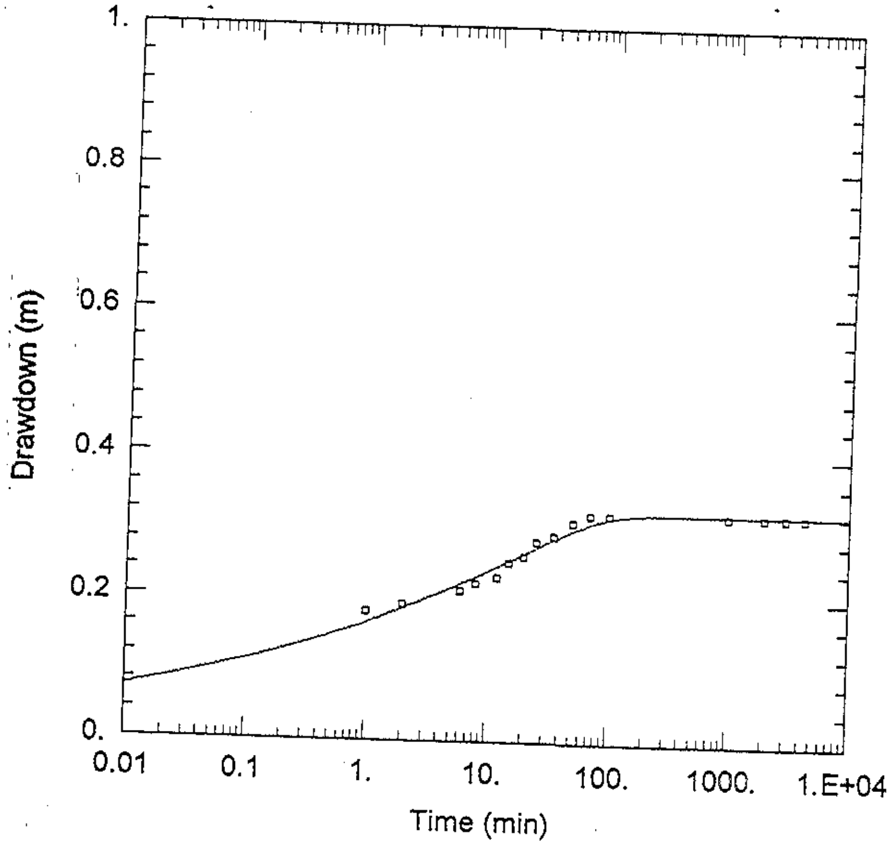


Well: bh16

Solution: Moench

T = 389 m^2/day

S = 0.0677



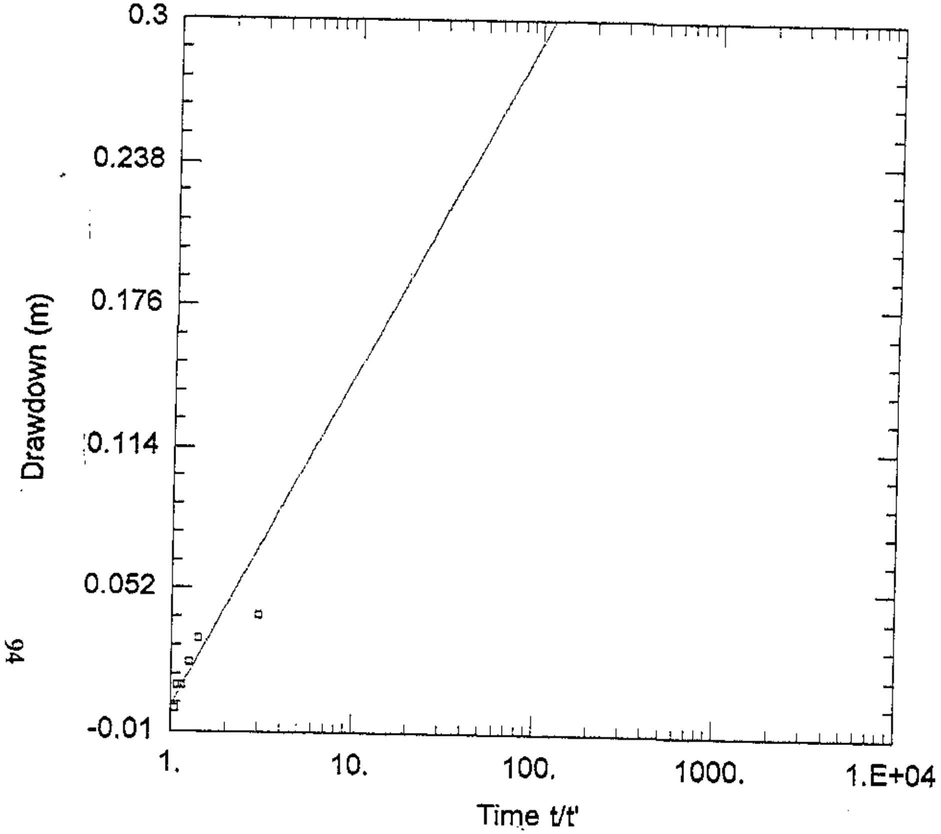
Well: bh18

Solution: Moench

T = 5386 m^2/day

S = 0.133

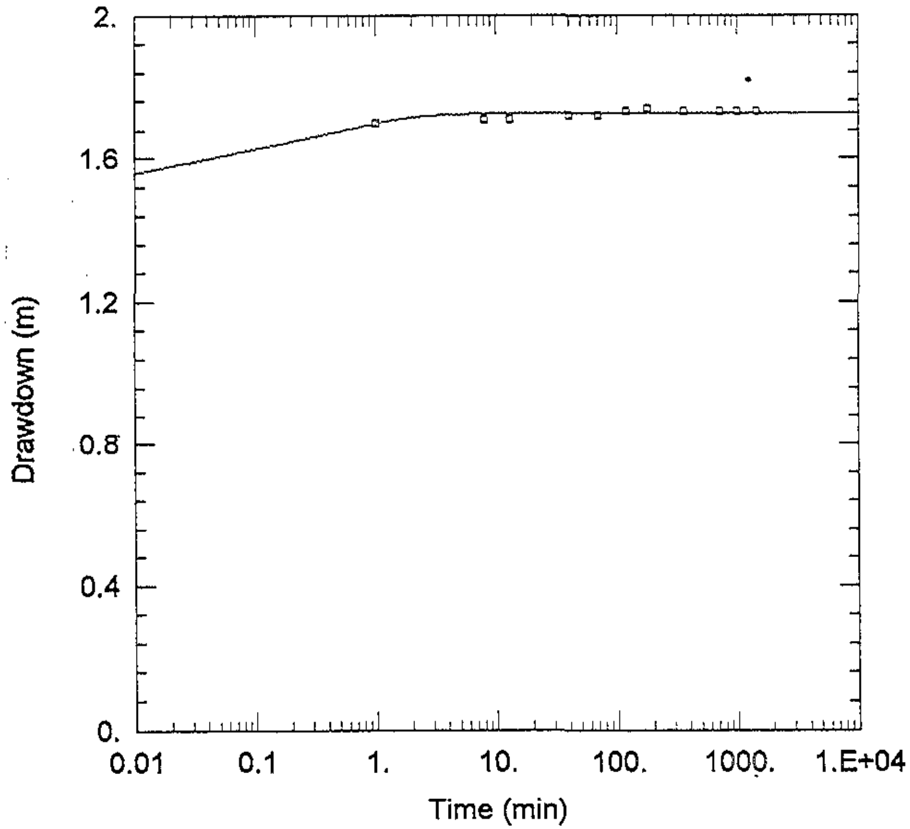
Appendix 2: continued



Well: bh19

Solution: Theis recovery

T = 9577 m^2/day



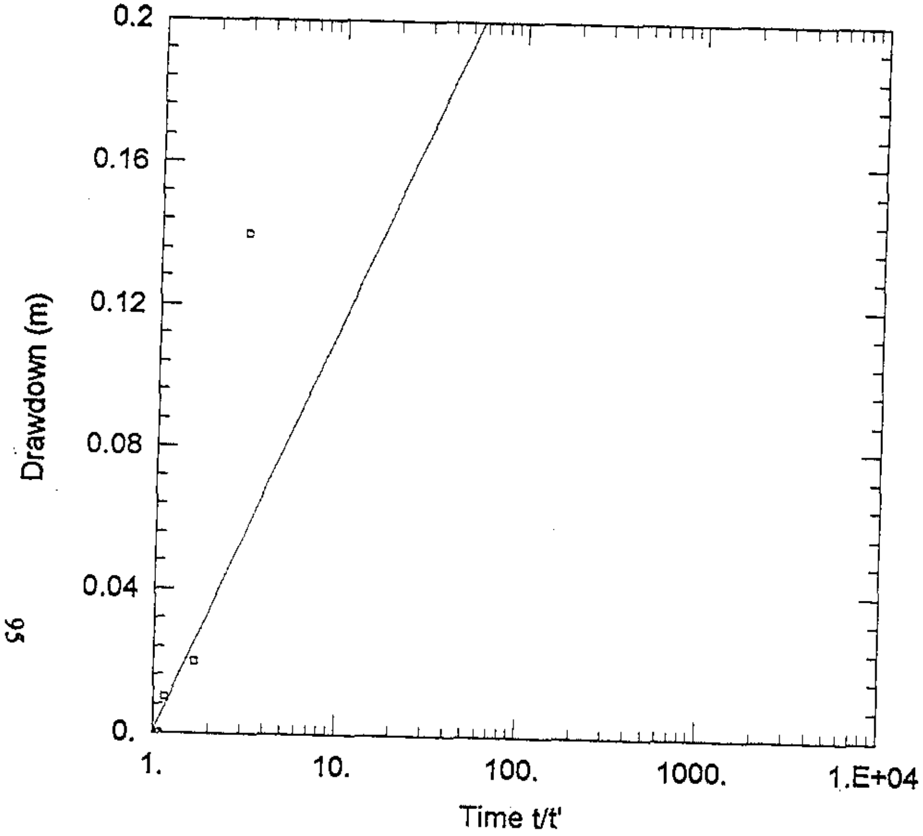
Well: bh19

Solution: Moench

T = 8891 m^2/day

S = 0.00025

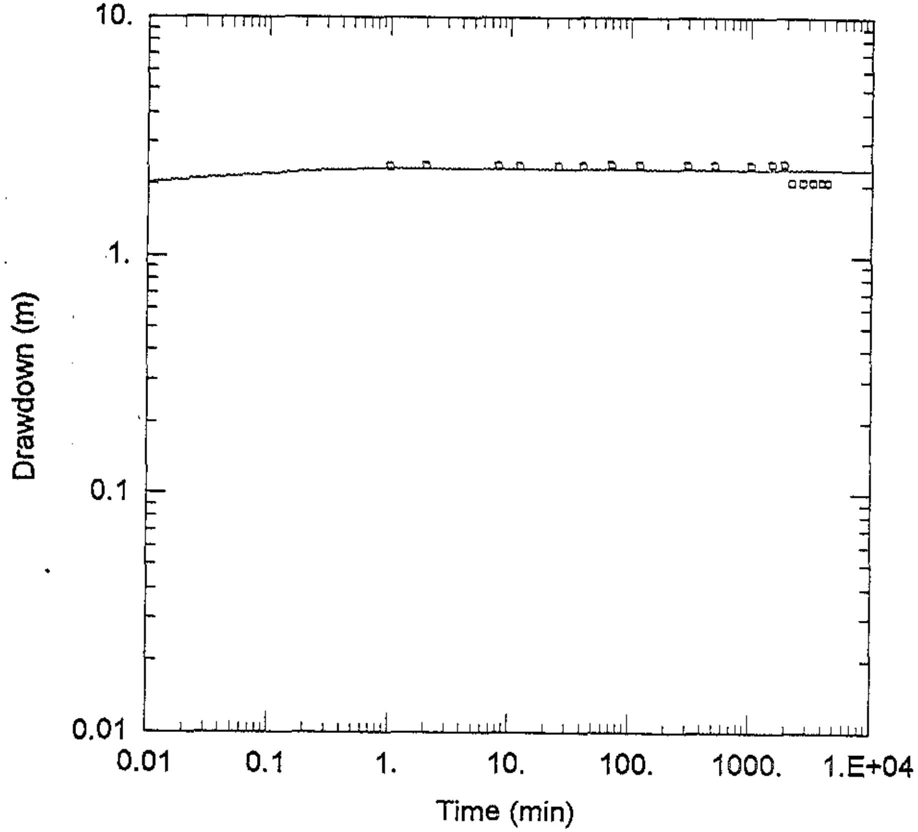
Appendix 2: continued



Well: bh21

Solution: Theis recovery

T = 10322 m^2/day



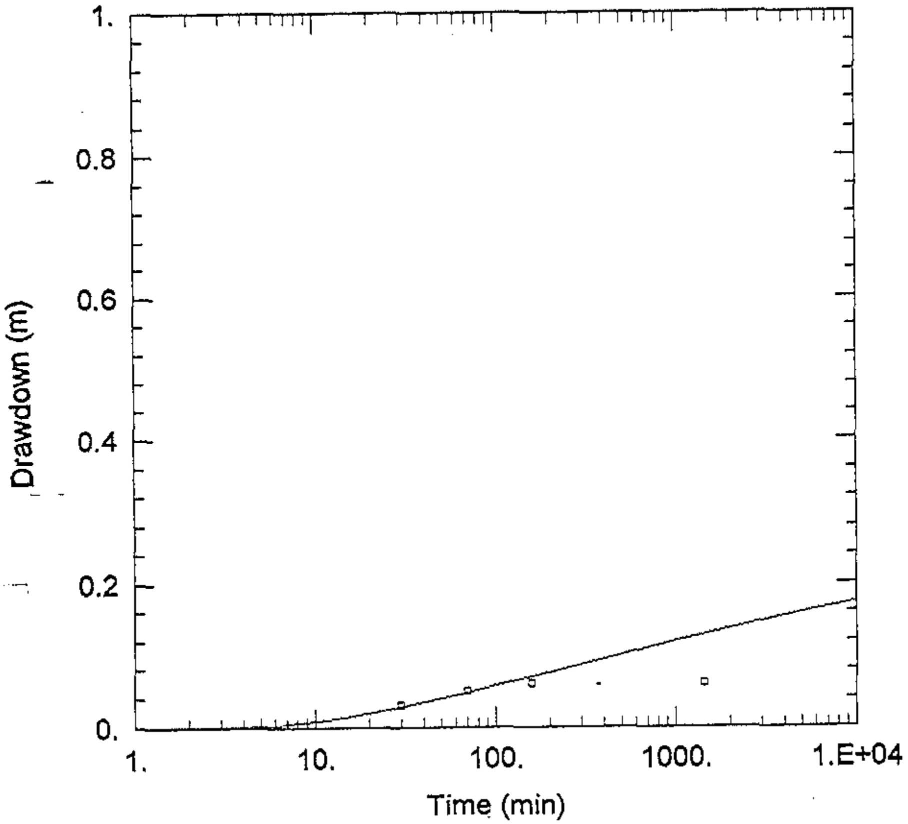
Well: bh22

Solution: Moench

T = 2909 m^2/day

S = 0.0001

Appendix 2: continued

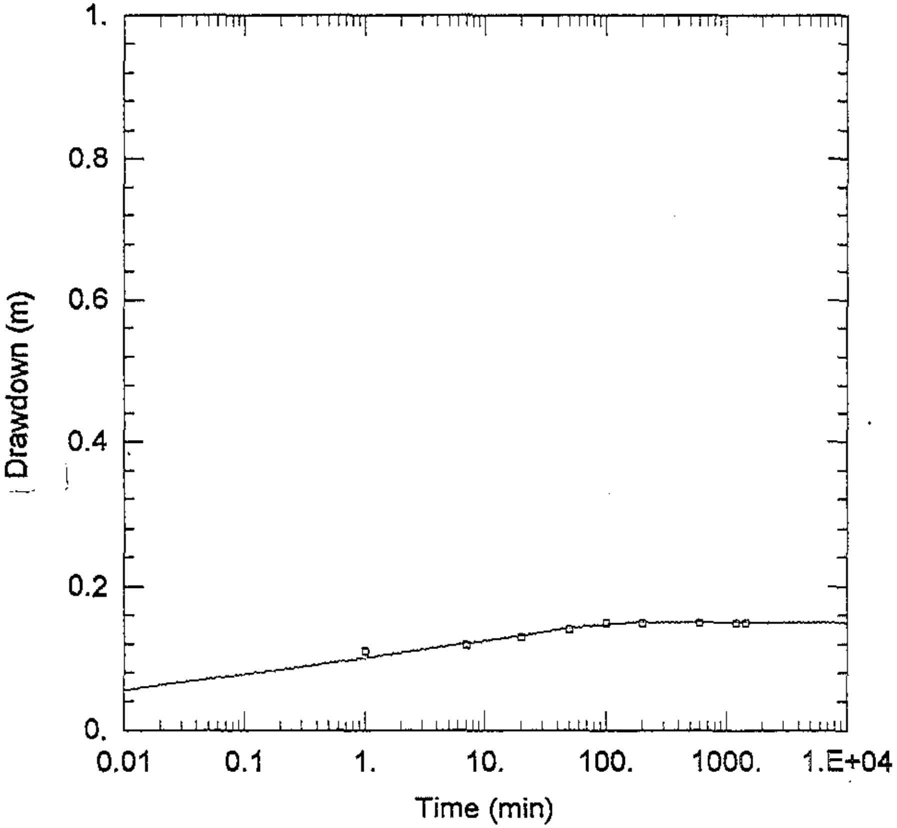


Well: bh25, obs. well: bh26

Solution: Hantush

T = 19037 m^2/day

S = 0.0037



Well: bh26

Solution: Moench

T = 21600 m^2/day

S = 0.0977

Appendix 2: continued

Current Drinking Water Standards

National Primary and Secondary Drinking Water Regulations

National Primary Drinking Water Regulations (NPDWRs or primary standards) are legally enforceable standards that apply to public water systems. Primary standards protect drinking water quality by limiting the levels of specific contaminants that can adversely affect public health and are known or anticipated to occur in public water systems. Table 1 divides these contaminants into Inorganic Chemicals, Organic Chemicals, Radionuclides, and Microorganisms. See Setting Standards for Safe Drinking Water to learn about EPA's standard-setting process.

National Primary Drinking Water Regulations

Contaminants	MCLG[1] (mg/L)[4]	MCL[2] or TT[3] (mg/L)[4]	Potential Health Effects from Ingestion of Water	Sources of Contaminant in Drinking Water
Inorganic Chemicals				
Antimony	0.006	0.006	Increase in blood cholesterol; decrease in blood glucose	Discharge from petroleum refineries; fire retardants; ceramics; electronics; solder
Arsenic	none[5]	0.05	Skin damage; circulatory system problems; increased risk of cancer	Discharge from semiconductor manufacturing; petroleum refining; wood preservatives; animal feed additives; herbicides; erosion of natural deposits
Asbestos (fiber >10 micrometers)	7 million fibers per Liter	7 MFL	Increased risk of developing benign intestinal polyps	Decay of asbestos cement in water mains; erosion of natural deposits
Barium	2	2	Increase in blood pressure	Discharge of drilling wastes; discharge from metal refineries; erosion of natural deposits

Appendix 3: Current Drinking Water standards based on U.S.E.P.A Office of Ground Water and Drinking water as of September 1998. Website http://www.epg.gov/OGWDW/wot/appa.html

Beryllium	0.004	0.004	Intestinal lesions	Discharge from metal refineries and coal-burning factories; discharge from electrical, aerospace, and defense industries
Cadmium	0.005	0.005	Kidney damage	Corrosion of galvanized pipes; erosion of natural deposits; discharge from metal refineries; runoff from waste batteries and paints
Chromium (total)	0.1	0.1	Some people who use water containing chromium well in excess of the MCL over many years could experience allergic dermatitis	Discharge from steel and pulp mills; erosion of natural deposits
Copper	1.3	Action Level=1.3; TT[6]	Short term exposure: Gastrointestinal distress. Long term exposure: Liver or kidney damage. Those with Wilson's Disease should consult their personal doctor if their water systems exceed the copper action level.	Corrosion of household plumbing systems; erosion of natural deposits; leaching from wood preservatives
Cyanide (as free cyanide)	0.2	0.2	Nerve damage or thyroid problems	Discharge from steel/metal factories; discharge from plastic and fertilizer factories
Fluoride	4.0	4.0	Bone disease (pain and tenderness of the bones); Children may get mottled teeth.	Water additive which promotes strong teeth; erosion of natural deposits; discharge from fertilizer and aluminum factories
Lead	zero	Action Level=0.015; TT[6]	Infants and children: Delays in physical or mental development. Adults: Kidney problems; high blood pressure	Corrosion of household plumbing systems; erosion of natural deposits
Inorganic Mercury	0.002	0.002	Kidney damage	Erosion of natural deposits; discharge from refineries and factories; runoff from landfills and cropland

Appendix 3: continued

Nitrate (measured as Nitrogen)	10	10	"Blue baby syndrome" in infants under six months - life threatening without immediate medical attention. Symptoms: Infant looks blue and has shortness of breath.	Runoff from fertilizer use; leaching from septic tanks, sewage; erosion of natural deposits
Nitrite (measured as Nitrogen)	1	1	"Blue baby syndrome" in infants under six months - life threatening without immediate medical attention. Symptoms: Infant looks blue and has shortness of breath.	Runoff from fertilizer use; leaching from septic tanks, sewage; erosion of natural deposits
Selenium	0.05	0.05	Hair or fingernail loss; numbness in fingers or toes; circulatory problems	Discharge from petroleum refineries; erosion of natural deposits; discharge from mines
Thallium	0.0005	0.002	Hair loss; changes in blood; kidney, intestine, or liver problems	Leaching from ore-processing sites; discharge from electronics, glass, and pharmaceutical companies

Organic Chemicals	**MCLG[1] (mg/L)[4]**	**MCL[2] or TT[3] (mg/L)[4]**	**Potential Health Effects from Ingestion of Water**	**Sources of Contaminant in Drinking Water**
Acrylamide	zero	TT[7]	Nervous system or blood problems; increased risk of cancer	Added to water during sewage/wastewater treatment
Alachlor	zero	0.002	Eye, liver, kidney or spleen problems; anemia; increased risk of cancer	Runoff from herbicide used on row crops
Atrazine	0.003	0.003	Cardiovascular system problems; reproductive difficulties	Runoff from herbicide used on row crops
Benzene	zero	0.005	Anemia; decrease in blood platelets; increased risk of cancer	Discharge from factories; leaching from gas storage tanks and landfills

Appendix 3: continued

Benzo(a)pyrene	zero	0.0002	Reproductive difficulties; increased risk of cancer	Leaching from linings of water storage tanks and distribution lines
Carbofuran	0.04	0.04	Problems with blood or nervous system; reproductive difficulties.	Leaching of soil fumigant used on rice and alfalfa
Carbon tetrachloride	zero	.005	Liver problems; increased risk of cancer	Discharge from chemical plants and other industrial activities
Chlordane	zero	0.002	Liver or nervous system problems; increased risk of cancer	Residue of banned termiticide
Chlorobenzene	0.1	0.1	Liver or kidney problems	Discharger from chemical and agricultural chemical factories
2,4-D	0.07	0.07	Kidney, liver, or adrenal gland problems	Runoff from herbicide used on row crops
Dalapon	0.2	0.2	Minor kidney changes	Runoff from herbicide used on rights of way
1,2-Dibromo-3-chloropropane (DBCP)	zero	0.0002	Reproductive difficulties; increased risk of cancer	Runoff/leaching from soil fumigant used on soybeans, cotton, pineapples, and orchards
o-Dichlorobenzene	0.6	0.6	Liver, kidney, or circulatory system problems	Discharge from industrial chemical factories
p-Dichlorobenzene	0.075	0.075	Anemia; liver, kidney or spleen damage; changes in blood	Discharge from industrial chemical factories
1,2-Dichloroethane	zero	0.005	Increased risk of cancer	Discharge from industrial chemical factories
1-1-Dichloroethylene	0.007	0.007	Liver problems	Discharge from industrial chemical factories
cis-1, 2-Dichloroethylene	0.07	0.07	Liver problems	Discharge from industrial chemical factories
trans-1,2-Dichloroethylene	0.1	0.1	Liver problems	Discharge from industrial chemical factories
Dichloromethane	zero	0.005	Liver problems; increased risk of cancer	Discharge from pharmaceutical and chemical factories
1-2-Dichloropropane	zero	0.005	Increased risk of cancer	Discharge from industrial chemical factories
Di(2-ethylhexyl)adipate	0.4	0.4	General toxic effects or reproductive difficulties	Leaching from PVC plumbing systems; discharge from chemical factories

Appendix 3: continued

Di(2-ethylhexyl)phthalate	zero	0.006	Reproductive difficulties; liver problems; increased risk of cancer	Discharge from rubber and chemical factories
Dinoseb	0.007	0.007	Reproductive difficulties	Runoff from herbicide used on soybeans and vegetables
Dioxin (2,3,7,8-TCDD)	zero	0.00000003	Reproductive difficulties; increased risk of cancer	Emissions from waste incineration and other combustion; discharge from chemical factories
Diquat	0.02	0.02	Cataracts	Runoff from herbicide use
Endothall	0.1	0.1	Stomach and intestinal problems	Runoff from herbicide use
Endrin	0.002	0.002	Nervous system effects	Residue of banned insecticide
Epichlorohydrin	zero	TT^{7}	Stomach problems; reproductive difficulties; increased risk of cancer	Discharge from industrial chemical factories; added to water during treatment process
Ethylbenzene	0.7	0.7	Liver or kidney problems	Discharge from petroleum refineries
Ethelyne dibromide	zero	0.00005	Stomach problems; reproductive difficulties; increased risk of cancer	Discharge from petroleum refineries
Glyphosate	0.7	0.7	Kidney problems; reproductive difficulties	Runoff from herbicide use
Heptachlor	zero	0.0004	Liver damage; increased risk of cancer	Residue of banned termiticide
Heptachlor epoxide	zero	0.0002	Liver damage; increased risk of cancer	Breakdown of hepatachlor
Hexachlorobenzene	zero	0.001	Liver or kidney problems; reproductive difficulties; increased risk of cancer	Discharge from metal refineries and agricultural chemical factories
Hexachlorocyclopentadiene	0.05	0.05	Kidney or stomach problems	Discharge from chemical factories
Lindane	0.0002	0.0002	Liver or kidney problems	Runoff/leaching from insecticide used on catttle, lumber, gardens
Methoxychlor	0.04	0.04	Reproductive difficulties	Runoff/leaching from insecticide used on fruits, vegetables, alfalfa, livestock

Appendix 3: continued

Oxamyl (Vydate)	0.2	0.2	Slight nervous system effects	Runoff/leaching from insecticide used on apples, potatoes, and tomatoes
Polychlorinated biphenyls (PCBs)	zero	0.0005	Skin changes; thymus gland problems; immune difficiencies; reproductive or nervous system difficulties; increased risk of cancer	Runoff from landfils; discharge of waste chemicals
Pentachlorophenol	zero	0.001	Liver or kidney problems; increased risk of cancer	Discharge from wood preserving factories
Picloram	0.5	0.5	Liver problems	Herbicide runoff
Simazine	0.004	0.004	Problems with blood	Herbicide runoff
Styrene	0.1	0.1	Liver, kidney, and circulatory problems	Discharge from rubber and plastic factories; leaching from landfills
Tetrachloroethylene	zero	0.005	Liver problems; increased risk of cancer	Leaching from PVC pipes; discharge from factories and dry cleaners
Toluene	1	1	Nervous system, kidney, or liver problems	Discharge from petroleum factories
Total Trihalomethanes (TTHMs)	none[5]	0.10	Liver, kidney or central nervous system problems; increased risk of cancer	Byproduct of drinking water disinfection
Toxaphene	zero	0.003	Kidney, liver, or thyroid problems; increased risk of cancer	Runoff/leaching from insecticide used on cotton and cattle
2,4,5-TP (Silvex)	0.05	0.05	Liver problems	Residue of banned herbicide
1,2,4-Trichlorobenzene	0.07	0.07	Changes in adrenal glands	Discharge from textile finishing factories
1,1,1-Trichloroethane	0.20	0.2	Liver, nervous system, or circulatory problems	Discharge from metal degreasing sites and other factories
1,1,2-Trichloroethane	0.003	0.005	Liver, kidney, or immune system problems	Discharge from industrial chemical factories
Trichloroethylene	zero	0.005	Liver problems; increased risk of cancer	Discharge from petroleum refineries
Vinyl chloride	zero	0.002	Increased risk of cancer	Leaching from PVC pipes; discharge from plastic factories
Xylenes (total)	10	10	Nervous system damage	Discharge from petroleum factories; discharge from chemical factories

Appendix 3: continued

Radionuclides	MCLG[1] (mg/L)[4]	MCL[2] or TT[3] (mg/L)[4]	Potential Health Effects from Ingestion of Water	Sources of Contaminant in Drinking Water
Beta particles and photon emitters	none[5]	4 millirems per year	Increased risk of cancer	Decay of natural and man-made deposits
Gross alpha particle activity	none[5]	15 picocuries per Liter (pCi/L)	Increased risk of cancer	Erosion of natural deposits
Radium 226 and Radium 228 (combined)	none[5]	5 pCi/L	Increased risk of cancer	Erosion of natural deposits

Microorganisms	MCLG[1] (mg/L)[4]	MCL[2] or TT[3] (mg/L)[4]	Potential Health Effects from Ingestion of Water	Sources of Contaminant in Drinking Water
Giardia lamblia	zero	TT[8]	Giardiasis, a gastroenteric disease	Human and animal fecal waste
Heterotrophic plate count	N/A	TT[8]	HPC has no health effects, but can indicate how effective treatment is at controlling microorganisms.	n/a
Legionella	zero	TT[8]	Legionnaire's Disease, commonly known as pneumonia	Found naturally in water; multiplies in heating systems
Total Coliforms (including fecal coliform and *E. Coli*)	zero	5.0%[9]	Used as an indicator that other potentially harmful bacteria may be present[10]	Human and animal fecal waste
Turbidity	N/A	TT[8]	Turbidity has no health effects but can interfere with disinfection and provide a medium for microbial growth. It may indicate the presence of microbes.	Soil runoff
Viruses (enteric)	zero	TT[8]	Gastroenteric disease	Human and animal fecal waste

Table 1

National Secondary Drinking Water Regulations

National Secondary Drinking Water Regulations (NSDWRs or secondary standards) are non-enforceable guidelines regulating contaminants that may cause cosmetic effects (such as skin or tooth discoloration) or aesthetic effects (such as taste, odor, or color) in drinking water. EPA recommends secondary standards to water systems but does not require systems to comply. However, states may choose to adopt them as enforceable standards. See Table 2.

Contaminant	Secondary Standard
Aluminum	0.05 to 0.2 mg/L
Chloride	250 mg/L
Color	15 (color units)
Copper	1.0 mg/L
Corrosivity	noncorrosive
Fluoride	2.0 mg/L
Foaming Agents	0.5 mg/L
Iron	0.3 mg/L
Manganese	0.05 mg/L
Odor	3 threshold odor number
pH	6.5-8.5
Silver	0.10 mg/L
Sulfate	250 mg/L
Total Dissolved Solids	500 mg/L
Zinc	5 mg/L

Table 2

Notes

[1] Maximum Contaminant Level Goal (MCLG) - The maximum level of a contaminant in drinking water at which no known or anticipated adverse effect on the health effect of persons would occur, and which allows for an adequate margin of safety. MCLGs are non-enforceable public health goals.

[2] Maximum Contaminant Level (MCL) - The maximum permissible level of a contaminant in water which is delivered to any user of a public water system. MCLs are enforceable standards. The margins of safety in MCLGs ensure that exceeding the MCL slightly does not pose significant risk to public health.

[3] Treatment Technique - An enforceable procedure or level of technical performance which public water systems must follow to ensure control of a contaminant.

Appendix 3: continued

[4] Units are in milligrams per Liter (mg/L) unless otherwise noted.

[5] MCLGs were not established before the 1986 Amendments to the Safe Drinking Water Act. Therefore, there is no MCLG for this contaminant.

[6] Lead and copper are regulated in a Treatment Technique which requires systems to take tap water samples at sites with lead pipes or copper pipes that have lead solder and/or are served by lead service lines. The action level, which triggers water systems into taking treatment steps if exceeded in more than 10% of tap water samples, for copper is 1.3 mg/L, and for lead is 0.015mg/L.

[7] Each water system must certify, in writing, to the state (using third-party or manufacturer's certification) that when acrylamide and epichlorohydrin are used in drinking water systems, the combination (or product) of dose and monomer level does not exceed the levels specified, as follows:

- **Acrylamide** = 0.05% dosed at 1 mg/L (or equivalent)
- **Epichlorohydrin** = 0.01% dosed at 20 mg/L (or equivalent)

[8] The Surface Water Treatment Rule requires systems using surface water or ground water under the direct influence of surface water to (1) disinfect their water, and (2) filter their water to meet criteria for avoiding filtration so that the following contaminants are controlled at the following levels:

- *Giardia lamblia:* 99.9% killed/inactivated
  Viruses: 99.99% killed/inactivated
- *Legionella:* No limit, but EPA believes that if *Giardia* and viruses are inactivated, *Legionella* will also be controlled.
- **Turbidity**: At no time can turbidity (cloudiness of water) go above 5 nephelolometric turbidity units (NTU); systems that filter must ensure that the turbidity go no higher than 1 NTU (0.5 NTU for conventional or direct filtration) in at least 95% of the daily samples for any two consecutive months.
- **HPC**: NO more than 500 bacterial colonies per milliliter.

[9] No more than 5.0% samples total coliform-positive in a month. (For water systems that collect fewer than 40 routine samples per month, no more than one sample can be total coliform-positive). Every sample that has total coliforms must be analyzed for fecal coliforms. There cannot be any fecal coliforms.

[10] Fecal coliform and *E. coli* are bacteria whose presence indicates that the water may be contaminated witih human animal wastes.

Sample	K	Na	Mg	Ca	Fe	NH4	PO4	NO2	F	NO3	Cl	SO4	HCO3	TDS	Error%
bh01	0.118	1.183	1.923	2.241	0.006	0.003	0	0.001	0.021	0.232	0.4	0	4.802	10.93	0.165
bh02	0.11	1.035	1.923	2.32	0.005	0	0	0	0.02	0.258	0.4	0	4.802	10.873	-0.8
bh03b	0.136	1.035	1.997	2.161	0.001	0	0	0	0.016	0.18	0.319	0	4.802	10.647	0.122
bh04	0.118	1.183	1.759	2.241	0	0	0.002	0.003	0.02	0.23	0.4	0	4.602	10.558	0.417
bh05b	0.11	1.093	0.954	2.241	0.002	0	0.002	0	0.032	0.052	0.4	0	4.002	8.888	-0.99
bh06	0.108	1.093	2.236	2.28	0.001	0	0.001	0	0.018	0.299	0.254	0.137	5.041	11.468	-0.279
bh07	0.108	1.131	2.277	2.201	0	0	0	0.033	0.017	0.221	0.24	0.158	5.122	11.508	-0.643
bh08	0.093	1.183	2.4	2.241	0	0	0.002	0	0.013	0.414	0.479	0	5.002	11.827	0.059
bh09	0.092	1.183	2.277	2.42	0	0	0.001	0	0.022	0.269	0.245	0.146	5.363	12.018	-0.616
bh10	0.101	1.331	2.318	1.996	0	0	0	0.003	0.012	0.148	0.4	0.154	5.002	11.465	0.236
bh11	0.076	1.331	2.162	2.32	0	0	0	0	0.017	0.341	0.319	0.358	4.802	11.726	0.443
bh12	0.101	1.183	1.999	2.959	0	0	0	0	0.027	0.158	0.327	0.135	5.602	12.491	-0.056
bh13	0.11	1.035	1.923	2.161	0	0	0	0	0.02	0.193	0.4	0	4.602	10.444	0.134
bh14	0.152	1.183	2.162	2.4	0	0	0	0	0.037	0	0.259	0.137	5.402	11.732	0.528
bh16	0.136	1.183	2.001	2.799	0	0	0	0.003	0.021	0.063	0.4	0.111	5.402	12.119	0.982
bh18	0.118	1.035	2.203	2.28	0	0	0	0.076	0.016	0.184	0.319	0	5.041	11.272	0
bh19	0.084	1.331	2.079	2.72	0	0	0	0	0.014	0.214	0.395	0.334	5.202	12.373	0.445
bh20	0.118	1.035	1.118	2.161	0	0	0	0	0.032	0.079	0.4	0	4.002	8.945	-0.906
bh21	0.101	1.183	1.997	2.64	0	0	0	0.002	0.018	0.222	0.4	0.556	4.802	11.921	-0.663
bh22	0.11	1.183	1.919	2.48	0	0	0	0.015	0.021	0.221	0.4	0.146	4.802	11.297	0.77
bh23	0.068	0.813	1.603	2.959	0	0	0	0.003	0.026	0.021	0.4	0	5.002	10.895	-0.083
bh24	0.118	1.775	1.603	2.001	0.014	0.004	0	0	0.02	0.198	0.4	0	4.802	10.935	0.869
bh25	0.11	1.183	1.923	2.48	0.003	0	0	0.091	0.021	0.151	0.4	0.184	4.714	11.26	1.226
bh26	0.101	1.183	1.919	2.48	0	0	0	0	0.029	0.198	0.338	0.154	4.802	11.204	1.446
EP6	0.079	1.257	2.162	2.161	0	0	0.001	0	0.023	0.262	0.231	0.133	4.963	11.272	0.408
EP7	0.118	1.553	2.318	1.482	0	0.001	0	0	0.015	0.264	0.358	0.27	4.562	10.941	0.027
EP8	0.084	1.592	1.94	1.981	0	0	0	0	0.024	0.264	0.259	0.164	4.963	11.271	-0.683

Appendix 4: Chemical analysis data of groundwater samples (meq/l) and Error (%) (AAWSA, 1996-97).

Sample	K	Na	Mg	Ca	Fe	Zn	F	NO3	Cl	SO4	HCO3	TDS	Error%
EP6	0.077	1.218	2.055	2.196	0	0.018	0.016	0.242	0.254	0.104	5.035	11.215	-0.776
EP7	0.077	1.218	2.055	2.196	0	0.015	0.016	0.242	0.254	0.146	4.936	11.155	-0.296
EP4	0.077	1.218	2.055	2.196	0	0.039	0.016	0.242	0.226	0.125	5.018	11.212	-0.375
SP	0.077	1.349	1.808	2.695	0	0	0.022	0.306	0.395	0.25	5.215	12.117	-2.137
MF	0.128	1.653	2.384	3.693	0	0	0.021	0.29	0.536	0.478	6.74	15.923	-1.299
SA	0.084	1.131	2.055	3.892	0	0.009	0.019	0.853	0.733	0.478	5.297	14.551	-1.436
RB	0.282	1.349	0.658	2.196	0.014	0	0.025	0.322	0.846	0.395	3.1	9.187	-2.057
RI	0.282	1.305	0.74	2.146	0.036	0	0.025	0.322	0.846	0.395	3.001	9.098	-0.879
RE	0.282	1.305	0.658	2.196	0.021	0	0.025	0.242	0.902	0.437	3.001	9.069	-1.599

Appendix 5: Chemical analysis of groundwater and Akaki river (meq/l) and Error (%) during the project.

Sample	sum of Cat. (meq/l)	Na+K	Mg	Ca	sum of Ani. (meq/l)	Cl+NO$_3$	SO$_4$	HCO$_3$
bh01	5.46	23.8	35.19	41.01	5.43	11.63	0	88.37
bh02	5.39	21.25	35.69	43.06	5.46	12.05	0	87.95
bh03b	5.33	21.97	37.47	40.55	5.3	9.41	0	90.59
bh04	5.3	24.54	33.18	42.28	5.23	12.04	0	87.96
bh05b	4.4	27.35	21.69	50.95	4.45	10.15	0	89.85
bh06	5.72	21.01	39.11	39.88	5.73	9.65	2.39	87.96
bh07	5.72	21.67	39.83	38.5	5.74	8.03	2.75	89.22
bh08	5.92	21.56	40.56	37.87	5.9	15.15	0	84.85
bh09	5.97	21.35	38.13	40.52	6.02	8.53	2.42	89.04
bh10	5.75	24.92	40.34	34.74	5.7	9.61	2.7	87.69
bh11	5.89	23.89	36.71	39.4	5.82	11.34	6.15	82.51
bh12	6.24	20.57	32.02	47.4	6.22	7.79	2.17	90.04
bh13	5.23	21.9	36.78	41.33	5.2	11.41	0	88.59
bh14	5.9	22.64	36.66	40.7	5.8	4.47	2.36	93.17
bh16	6.12	21.56	32.7	45.74	5.98	7.75	1.86	90.39
bh18	5.64	20.46	39.09	40.45	5.54	9.07	0	90.93
bh19	6.21	22.77	33.46	43.77	6.15	9.91	5.44	84.65
bh20	4.43	26.02	25.23	48.8	4.48	10.69	0	89.31
bh21	5.92	21.69	33.73	44.59	5.98	10.4	9.3	80.3
bh22	5.69	22.72	33.71	43.57	5.57	11.15	2.62	86.23
bh23	5.44	16.19	29.45	54.36	5.42	7.76	0	92.24
bh24	5.5	34.44	29.16	36.4	5.4	11.07	0	88.93
bh25	5.7	22.7	33.76	43.54	5.45	10.11	3.38	86.51
bh26	5.7	22.59	33.77	43.64	5.49	9.76	2.8	87.44
EP6	5.66	23.61	38.2	38.19	5.59	8.82	2.38	88.8
EP7	5.47	30.54	42.37	27.09	5.45	11.4	4.95	83.65
EP8	5.6	29.94	34.66	35.39	5.65	9.26	2.9	87.84
EP6	5.55	23.35	37.05	39.6	5.64	8.8	1.85	89.35
EP7	5.55	23.35	37.05	39.6	5.58	8.89	2.62	88.49
EP4	5.55	23.35	37.05	39.6	5.61	8.34	2.23	89.43
SP	5.93	24.05	30.49	45.45	6.17	11.37	4.05	84.58
MF	7.86	22.66	30.34	47	8.04	10.27	5.94	83.79
SA	7.16	16.96	28.69	54.34	7.36	21.55	6.49	71.96
RB	4.49	36.37	14.67	48.96	4.66	25.05	8.47	66.48
RI	4.47	35.48	16.54	47.98	4.56	25.59	8.65	65.75
RE	4.44	35.74	14.82	49.45	4.58	24.97	9.54	65.5

Appendix 6: Major cations and anions of groundwaters and river water (%meq/l).

Station:, 6345000 Addis Ababa Ethiopia
Latitude:, 9.00, N Longitude: 38.37, E Altitude: 2360 m

year	month	prec	trit	deut	oxyg
,,,,,,,,,,,,					
1961	1	24			
1961	2	25			
1961	3	68		-10.6	-2.70
1961	4	95		17.4	.10
1961	5	50		38.5	2.50
1961	6	105		7.5	-1.50
1961	7	228			
1961	8	263			
1961	9	174			
1961	10	41			
1961	11	3			
1961	12	15			
1962	1				
1962	2				
1962	3				
1962	4				
1962	5				
1962	6				
1962	7				
1962	8				
1962	9				
1962	10				
1962	11				
1962	12				
1963	1				
1963	2				
1963	3				
1963	4				
1963	5				
1963	6				
1963	7				
1963	8				
1963	9				
1963	10				
1963	11				
1963	12				
1964	1	24			
1964	2	25			
1964	3	100			
1964	4	95			
1964	5	117			
1964	6	198			
1964	7	270			
1964	8	124		-35.4	-5.30
1964	9	200		3.1	-1.20
1964	10	54			
1964	11	1			
1964	12	50	56.20		
1965	1	25	189.00	30.5	3.10
1965	2	6	154.00		
1965	3	38	111.00	-20.4	-4.60
1965	4	53	112.00	25.2	1.50
1965	5	9	332.00	36.5	
1965	6	62			
1965	7	275			
1965	8	276			
1965	9	116			
1965	10	113			

Appendix 7: Tritium and stable isotopic composition of Addis Ababa rain water in TU and per mil respectively. (IAEA Vienna).

```
1965,      11,       3,          ,         ,         ,
1965,      12,      15,          ,         ,         ,
1966,       1,       0,          ,         ,         ,
1966,       2,      25,          ,         ,         ,
1966,       3,      80,          ,         ,         ,
1966,       4,      84,          ,         ,         ,
1966,       5,      50,          ,         ,         ,
1966,       6,     138,          ,         ,         ,
1966,       7,     292,          ,         ,         ,
1966,       8,     330,          ,         ,         ,
1966,       9,     150,          ,         ,         ,
1966,      10,      57,          ,         ,         ,
1966,      11,       3,          ,         ,         ,
1966,      12,      15,          ,         ,         ,
1967,       1,      25,          ,         ,         ,
1967,       2,      25,    39.30,          ,         ,
1967,       3,      68,          ,         ,         ,
1967,       4,      93,          ,         ,         ,
1967,       5,     114,          ,         ,         ,
1967,       6,      95,          ,         ,         ,
1967,       7,     179,          ,         ,         ,
1967,       8,     294,          ,         ,         ,
1967,       9,     233,          ,         ,         ,
1967,      10,      36,          ,         ,         ,
1967,      11,      60,          ,         ,         ,
1967,      12,       0,          ,         ,         ,
1968,       1,      12,          ,         ,         ,
1968,       2,     139,          ,         ,         ,
1968,       3,      35,          ,         ,         ,
1968,       4,     229,          ,         ,         ,
1968,       5,      33,          ,         ,         ,
1968,       6,     140,          ,         ,         ,
1968,       7,     228,          ,         ,         ,
1968,       8,     229,          ,         ,         ,
1968,       9,     181,          ,         ,         ,
1968,      10,       5,          ,         ,         ,
1968,      11,       0,          ,         ,         ,
1968,      12,       0,          ,         ,         ,
1969,       1,      43,    31.50,      11.3,      .05,
1969,       2,      87,    39.20,       7.7,    -1.46,
1969,       3,      96,    43.20,       9.5,      .80,
1969,       4,     110,    47.40,      18.0,     1.11,
1969,       5,     117,    90.20,      17.4,      .99,
1969,       6,     146,   122.30,      27.6,     1.40,
1969,       7,     233,   168.50,      -6.4,    -2.85,
1969,       8,     312,   160.70,     -12.4,    -3.58,
1969,       9,     161,   119.80,      16.6,     -.29,
1969,      10,       1,          ,         ,         ,
1969,      11,       4,          ,         ,         ,
1969,      12,       0,          ,         ,         ,
1970,       1,      43,    29.00,       7.1,     -.79,
1970,       2,      60,          ,       7.5,      .13,
1970,       3,     232,    39.50,      19.5,      .78,
1970,       4,      41,   115.40,      27.7,     2.62,
1970,       5,      18,    91.70,      28.1,     1.70,
1970,       6,      86,   165.40,      27.7,     2.60,
1970,       7,     303,   181.70,     -17.1,    -3.60,
1970,       8,     425,   153.30,     -20.4,    -4.63,
1970,       9,     214,    95.50,      -4.3,         ,
1970,      10,       0,          ,         ,         ,
1970,      11,       0,          ,         ,         ,
1970,      12,       0,          ,         ,         ,
1971,       1,      24,          ,         ,         ,
```

Appendix 7: continued

```
1971,         2,         0,           ,          ,          ,
1971,         3,        15,           ,          ,          ,
1971,         4,        70,      68.50,          ,      2.38,
1971,         5,       201,      80.00,          ,       .33,
1971,         6,       132,     135.10,          ,      2.95,
1971,         7,       241,     142.30,          ,       .33,
1971,         8,       340,     157.80,          ,     -2.52,
1971,         9,       127,      81.70,          ,     -1.53,
1971,        10,         8,           ,          ,          ,
1971,        11,        11,           ,          ,          ,
1971,        12,        14,           ,          ,          ,
1972,         1,        21,      30.20,      25.7,      1.23,
1972,         2,        72,           ,          ,          ,
1972,         3,        43,      31.20,       6.2,      -.89,
1972,         4,       180,           ,          ,          ,
1972,         5,        40,           ,          ,          ,
1972,         6,       124,           ,          ,          ,
1972,         7,       230,      66.10,          ,     -2.45,
1972,         8,       142,      81.80,      20.7,       .55,
1972,         9,       115,      41.40,      20.0,       .16,
1972,        10,         0,           ,          ,          ,
1972,        11,        16,      27.10,          ,          ,
1972,        12,         1,           ,          ,          ,
1973,         1,         0,           ,          ,          ,
1973,         2,         2,           ,      37.5,      5.13,
1973,         3,         2,           ,          ,          ,
1973,         4,        34,      19.20,          ,          ,
1973,         5,       139,      19.20,      36.1,      2.14,
1973,         6,       107,      58.10,      27.9,      1.42,
1973,         7,       268,      86.90,     -16.8,     -4.01,
1973,         8,       346,      60.70,     -17.6,     -3.95,
1973,         9,       270,      45.40,      14.9,      -.65,
1973,        10,        50,           ,          ,          ,
1973,        11,         0,           ,          ,          ,
1973,        12,        53,           ,          ,          ,
1974,         1,         0,           ,          ,          ,
1974,         2,        32,       1.80,       7.9,       .23,
1974,         3,       123,           ,          ,          ,
1974,         4,         9,           ,          ,          ,
1974,         5,       125,      29.10,      -9.4,     -2.43,
1974,         6,       136,           ,          ,     -5.90,
1974,         7,       265,           ,        .7,       .05,
1974,         8,       331,           ,      -7.5,     -3.24,
1974,         9,       229,           ,      15.6,      -.34,
1974,        10,         4,           ,          ,          ,
1974,        11,         0,           ,          ,          ,
1974,        12,         0,           ,          ,          ,
1975,         1,         0,           ,          ,          ,
1975,         2,        20,           ,          ,          ,
1975,         3,        28,           ,      27.2,      3.03,
1975,         4,        33,           ,      29.5,      1.96,
1975,         5,        54,           ,      33.2,      1.98,
1975,         6,       134,           ,      14.8,       .09,
1975,         7,       272,           ,     -14.4,     -3.15,
1975,         8,       184,           ,     -37.9,     -6.93,
1975,         9,       182,           ,     -11.5,     -3.00,
1975,        10,        17,           ,          ,          ,
1975,        11,         0,           ,          ,          ,
1975,        12,         0,           ,          ,          ,
1976,         1,         0,           ,          ,          ,
1976,         2,        61,           ,      22.9,      2.68,
1976,         3,        44,           ,      21.3,       .74,
1976,         4,        95,           ,      32.4,      1.82,
```

Appendix 7: continued

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1976,       5,      113,           ,     13.3,    -1.10,
1976,       6,      108,           ,         ,     1.30,
1976,       7,      278,           ,     10.3,     -.50,
1976,       8,      272,           ,    -10.1,    -2.65,
1976,       9,       25,           ,    -24.2,    -4.91,
1976,      10,        3,           ,     -8.7,    -2.74,
1976,      11,       62,           ,      5.7,    -1.94,
1976,      12,        0,           ,         ,         ,
1977,       1,       56,           ,         ,         ,
1977,       2,       40,           ,         ,         ,
1977,       3,       68,           ,         ,         ,
1977,       4,       66,           ,         ,         ,
1977,       5,      146,           ,         ,         ,
1977,       6,      155,           ,         ,         ,
1977,       7,      255,           ,         ,         ,
1977,       8,      279,           ,         ,         ,
1977,       9,      134,           ,         ,         ,
1977,      10,      273,           ,         ,         ,
1977,      11,        1,           ,         ,         ,
1977,      12,        0,           ,         ,         ,
1978,       1,        2,           ,         ,         ,
1978,       2,       63,           ,         ,         ,
1978,       3,       31,           ,         ,         ,
1978,       4,       80,           ,         ,         ,
1978,       5,       31,           ,         ,         ,
1978,       6,      117,           ,         ,         ,
1978,       7,      208,           ,         ,         ,
1978,       8,      361,           ,         ,         ,
1978,       9,      111,           ,         ,         ,
1978,      10,       39,           ,         ,         ,
1978,      11,        0,           ,         ,         ,
1978,      12,        3,           ,         ,         ,
1979,       1,      128,           ,         ,         ,
1979,       2,       19,           ,         ,         ,
1979,       3,       74,           ,         ,         ,
1979,       4,       85,           ,         ,         ,
1979,       5,      103,           ,         ,         ,
1979,       6,      140,           ,         ,         ,
1979,       7,      316,           ,         ,         ,
1979,       8,      186,           ,         ,         ,
1979,       9,      225,           ,         ,         ,
1979,      10,        0,           ,         ,         ,
1979,      11,        0,           ,         ,         ,
1979,      12,       16,           ,         ,         ,
1980,       1,       23,           ,         ,         ,
1980,       2,       37,           ,         ,         ,
1980,       3,       45,           ,         ,         ,
1980,       4,       89,           ,         ,         ,
1980,       5,       54,           ,         ,         ,
1980,       6,      126,           ,         ,         ,
1980,       7,      365,           ,         ,         ,
1980,       8,      297,           ,         ,         ,
1980,       9,      182,           ,         ,         ,
1980,      10,       52,           ,         ,         ,
1980,      11,        0,           ,         ,         ,
1980,      12,        0,           ,         ,         ,
1981,       1,        0,           ,         ,         ,
1981,       2,       76,           ,         ,         ,
1981,       3,      176,           ,         ,         ,
1981,       4,       83,           ,         ,         ,
1981,       5,        4,           ,         ,         ,
1981,       6,       50,           ,         ,         ,
1981,       7,      267,           ,         ,         ,
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Appendix 7: continued

```
1981,     8,    321,         ,        ,        ,
1981,     9,    182,         ,        ,        ,
1981,    10,     13,         ,        ,        ,
1981,    11,      0,         ,        ,        ,
1981,    12,      5,         ,        ,        ,
1982,     1,     49,         ,    17.9,     .47,
1982,     2,     81,         ,    30.4,    2.22,
1982,     3,     58,         ,    28.4,    2.55,
1982,     4,    104,         ,    22.0,    1.07,
1982,     5,    116,         ,   -16.5,   -3.30,
1982,     6,     32,         ,    25.2,    3.15,
1982,     7,    259,         ,    15.4,     .20,
1982,     8,    258,         ,   -30.6,   -5.45,
1982,     9,    134,         ,    13.4,    -.03,
1982,    10,     64,         ,   -24.9,   -4.86,
1982,    11,     43,         ,   -33.8,   -5.87,
1982,    12,     12,         ,     5.4,   -1.36,
1983,     1,       ,         ,        ,        ,
1983,     2,       ,         ,        ,        ,
1983,     3,       ,         ,        ,        ,
1983,     4,       ,         ,        ,        ,
1983,     5,       ,         ,        ,        ,
1983,     6,       ,         ,        ,        ,
1983,     7,       ,         ,        ,        ,
1983,     8,       ,         ,        ,        ,
1983,     9,       ,         ,        ,        ,
1983,    10,       ,         ,        ,        ,
1983,    11,       ,         ,        ,        ,
1983,    12,       ,         ,        ,        ,
1984,     1,      0,         ,        ,        ,
1984,     2,      8,     7.50,     4.9,     .54,
1984,     3,     10,    10.30,    35.7,    5.42,
1984,     4,      9,    10.50,    42.7,    6.13,
1984,     5,    119,     7.10,     4.1,    -.88,
1984,     6,    125,    11.30,    19.5,     .55,
1984,     7,    296,    16.30,    12.4,     .10,
1984,     8,    296,    16.20,     2.1,     .30,
1984,     9,    142,    12.70,        ,        ,
1984,    10,      0,         ,        ,        ,
1984,    11,      4,     7.40,     4.1,    -.21,
1984,    12,     16,         ,        ,        ,
1985,     1,     14,     6.20,    -1.4,   -1.21,
1985,     2,      0,         ,        ,        ,
1985,     3,     22,     6.40,        ,        ,
1985,     4,     96,     7.00,     9.4,    -.53,
1985,     5,     84,     7.90,        ,        ,
1985,     6,    147,    13.80,    27.0,    1.69,
1985,     7,    260,    16.60,     5.2,   -1.02,
1985,     8,    326,    15.10,   -13.9,   -3.05,
1985,     9,    205,    10.10,    17.2,     .16,
1985,    10,     58,    10.40,        ,        ,
1985,    11,      3,    11.40,        ,        ,
1985,    12,      2,    25.00,    23.2,    1.83,
1986,     1,      0,         ,        ,        ,
1986,     2,       ,         ,        ,        ,
1986,     3,       ,    14.90,        ,        ,
1986,     4,       ,     7.40,    26.4,    1.89,
1986,     5,    131,         ,        ,        ,
1986,     6,    186,    11.30,     6.3,    -.66,
1986,     7,    214,    15.00,    14.9,     .94,
1986,     8,    263,    14.90,     -.5,   -1.97,
1986,     9,    129,         ,        ,        ,
1986,    10,     36,         ,        ,        ,
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Appendix 7: continued

```
1986,       11,         0,          ,         ,          ,
1986,       12,         0,          ,         ,          ,
1987,        1,         0,          ,         ,          ,
1987,        2,        54,     6.60,         ,          ,
1987,        3,       235,          ,         ,          ,
1987,        4,        97,          ,         ,          ,
1987,        5,       177,     4.60,    -32.7,     -5.45,
1987,        6,        82,    11.80,     34.6,      4.87,
1987,        7,       312,    11.70,     27.1,      1.26,
1987,        8,       167,    12.10,     10.4,      -.92,
1987,        9,       114,     9.30,     15.8,       .27,
1987,       10,        21,     4.80,         ,          ,
1987,       11,         0,          ,         ,          ,
1987,       12,         0,          ,         ,          ,
1988,        1,          ,          ,         ,          ,
1988,        2,          ,          ,         ,          ,
1988,        3,          ,          ,         ,          ,
1988,        4,          ,          ,         ,          ,
1988,        5,          ,          ,         ,          ,
1988,        6,          ,          ,         ,          ,
1988,        7,          ,          ,         ,          ,
1988,        8,          ,          ,         ,          ,
1988,        9,          ,          ,         ,          ,
1988,       10,          ,          ,         ,          ,
1988,       11,          ,          ,         ,          ,
1988,       12,          ,          ,         ,          ,
1989,        1,          ,          ,         ,          ,
1989,        2,          ,          ,         ,          ,
1989,        3,          ,          ,         ,          ,
1989,        4,          ,          ,         ,          ,
1989,        5,          ,          ,         ,          ,
1989,        6,          ,          ,         ,          ,
1989,        7,          ,          ,         ,          ,
1989,        8,          ,          ,         ,          ,
1989,        9,          ,          ,         ,          ,
1989,       10,          ,          ,         ,          ,
1989,       11,          ,          ,         ,          ,
1989,       12,          ,          ,         ,          ,
1990,        1,         1,    13.30,         ,          ,
1990,        2,       152,     3.60,     13.6,      -.76,
1990,        3,        60,     2.00,     14.2,      -.31,
1990,        4,       146,     5.90,      4.1,     -1.85,
1990,        5,        20,     2.50,     32.9,      1.67,
1990,        6,        84,     6.80,     41.9,      2.57,
1990,        7,       215,     9.90,     -7.3,     -2.76,
1990,        8,       268,    12.00,     11.0,      -.29,
1990,        9,       184,     7.40,     12.8,      -.34,
1990,       10,        16,    10.90,     27.0,      2.61,
1990,       11,         6,     7.10,     35.3,      3.89,
1990,       12,         0,          ,         ,          ,
1991,        1,         1,     6.80,      2.2,     -1.09,
1991,        2,        69,     5.70,     24.3,       .99,
1991,        3,       105,          ,      9.4,      -.49,
1991,        4,        34,    18.10,     53.3,          ,
1991,        5,        55,     6.10,         ,          ,
1991,        6,       190,    10.60,     18.1,       .19,
1991,        7,       248,    12.10,     -6.0,     -2.61,
1991,        8,       133,    11.20,     -9.0,     -3.08,
1991,        9,       120,          ,         ,          ,
1991,       10,         3,    16.10,     32.7,          ,
1991,       11,         0,          ,         ,          ,
1991,       12,        50,    13.60,     -9.2,     -2.45,
1992,        1,          ,     3.70,     18.8,       .90,
```

Appendix 7: continued

```
1992,      2,     33,    7.40,    18.7,    1.09,
1992,      3,     20,    5.10,    28.3,    3.09,
1992,      4,     40,    3.70,    24.0,    1.40,
1992,      5,     55,    4.00,    16.0,     .52,
1992,      6,    108,    7.00,    18.6,     .63,
1992,      7,     78,    9.50,     6.6,   -1.19,
1992,      8,    138,    9.70,   -40.1,   -7.20,
1992,      9,    122,    8.70,     3.7,   -1.48,
1992,     10,     69,   10.90,    24.0,    1.93,
1992,     11,      0,        ,        ,        ,
1992,     12,      1,    2.40,   -11.5,   -2.85,
1993,      1,     11,    5.80,    13.6,     .34,
1993,      2,     67,    5.10,     9.1,   -1.05,
1993,      3,     16,    5.10,    48.1,    5.23,
1993,      4,    158,    4.10,    13.1,    -.25,
1993,      5,     97,    4.90,    12.9,    -.19,
1993,      6,    208,    8.30,    19.6,     .69,
1993,      7,    274,   10.00,     5.2,   -1.40,
1993,      8,    427,    8.50,     6.4,   -1.49,
1993,      9,    243,    6.50,    26.1,     .99,
1993,     10,     62,    5.30,     -.9,   -1.63,
1993,     11,      0,        ,        ,        ,
1993,     12,      5,    3.60,     7.7,    -.47,
1994,      1,      0,        ,        ,        ,
1994,      2,      0,        ,        ,        ,
1994,      3,     82,    4.90,    19.0,     .98,
1994,      4,     70,    5.30,    22.3,    2.19,
1994,      5,     31,   16.20,    12.3,     .82,
1994,      6,    112,    8.60,    38.1,    2.78,
1994,      7,    306,    8.60,   -24.0,   -4.41,
1994,      8,    199,    9.30,   -29.1,   -4.81,
1994,      9,    139,    7.60,     5.0,    -.85,
1994,     10,      1,    9.40,    10.0,    1.38,
1994,     11,     11,    6.30,   -45.0,   -5.20,
1994,     12,      0,        ,        ,        ,
1995,      1,      0,        ,        ,        ,
1995,      2,     72,    6.00,    11.5,    -.19,
1995,      3,     42,   27.32,    13.5,     .20,
1995,      4,    174,    5.90,    18.0,     .20,
1995,      5,     68,    6.84,    29.3,    2.15,
1995,      6,    103,    8.32,    37.6,    3.19,
1995,      7,    182,    9.21,    -5.2,   -2.78,
1995,      8,    315,    7.67,    -4.9,   -2.68,
1995,      9,    136,    6.63,    17.4,     .62,
1995,     10,      1,    4.56,    47.7,    5.26,
1995,     11,      0,        ,        ,        ,
1995,     12,     48,     .98,     6.2,    -.11,
```

Appendix 7: continued