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HYDROGEOLOGY OF THE AYNALEM WELLFIELD, TIGRAY, NORTHERN ETHIOPIA.

A THESIS

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MASTER OF SCIENCE IN GEOLOGY

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ABEDLWASSIE HUSSIEN

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ABSTRACT

The shortage of drinking water is one of the critical social issues concerning the Mekele town. Groundwater is the only source to fulfil the need so far. However, there is no sufficient water supply for the town. Therefore a detailed hydrogeological investigations of the well field supplying the Mekele Town and its reserve assessment with respect to the increasing demand is very important.

In light of this and based on the available data of well logs, pumping tests, meteorological data and field observations an attempt has been made to map the area and characterize the aquifer parameters. The study area constitute limestone, shale & marl, and dolerite as main units with variable hydrogeological importance. Limestone is the main aquifer unit with hydraulic conductivity values ranging from 29-74 m/day while the dolerite is the second important aquifer with hydraulic conductivity values 0.02-1 m/day. The role of the shale and marl is confined to that part of the recharge and transition zone.

Precipitation is the most important source of recharge. Nine percent (57 mm) of the total rainfall is detained by the soil and ultimately joins the groundwater. Channel loss manifested by the disappearance and reappearance of the Aynalem river the second important component of groundwater recharge. The presence of ponds in the recharge area and their construction on fault zones and cavernous limestones also contribute significant amount of water.

Two main fault systems affect the area. The role of these structures is not only confined in controlling drainage patterns but also serve as groundwater conduits into and out of the catchment. The presence of cavernous features play an important role in the groundwater movement. Bedding planes and joints are also important vertical and horizontal pathways.

Water quality assessment on a number of samples revealed that the well filed is entirely free from antropogenic pollution. They are basically within the acceptable limits for the use as drinking water and for irrigation. The water type varies form calcium carbonate to calcium sulfate as one goes form east to west indicating groundwater evolution.

The results of water balance calculations and rough groundwater reserve estimation were compared with the population growth rate of Mekele and the corresponding estimated water demand. The outcome of this analysis can be stated as that the groundwater recharge by far overweighs the need.

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CHAPTER ONE

INTRODUCTION

1.1. Background of the study

Understanding the hydrogeology of the Aynalem catchment is important in solving the problem of water supply of the town of Mekele, thereby defining the possible degree of groundwater exploitation. Such a study will be useful to promote the existing hydrogeological knowledge of areas with similar geological setting and tectonic environment. Further more, the data and the results obtained from this research will be useful in planning future water resource development and environmental protection.

1.2. Previous investigations

The Mekele outlier has been a site of hydrogeological studies for the last three decades. Hydrogeological assessment of the central part of Tigray with the aim of providing reliable basic climatic and hydrological data, and collection of data for selected projects were carried out by Mecdonald, et *al.* (1975) . Other studies concentrated primarily to locate well sites for irrigation purpose (Beyth and Shachnai , 1970) . Subsequently, with the increasing water supply demand of the Mekele town, a hydrogeological and geophysical investigation to asses the groundwater potential has been carried out by Tesfaye Chernet *et al. (1980)* and Vernier (1985).

- To perform water balance evaluation of the study area based on the available hydometeorological data.

- To determine the recharge mechanism of the aquifer and identify the role of the different structural features in controlling ground water movement.

- To study the hydraulic connection of different aquifers (if any) based on the water chemistry.

1.4. Methodology

To meet the general and specific objectives the following methodologies were followed:

- **Office Work:** It encompasses all preparations for field work including collection of relevant data (hydometeorological data, published and unpublished reports, aerial photographs, topographic maps, etc), literature review, and preparation of preliminary geological map from aerial photo interpretation.

- **Field work:** It was carried out between January 26 to February 29 and May 13 to May 23, 2000. It was conducted to prepare geological and hydrogeological maps, field river discharge measurements, identify and locate the bore holes, and water sample collection for chemical analysis. The second trip was to check the uncertainties in the compilation of the previous field works and collection of additional data.

- **Post fieldwork:** This stage is mainly focused on the analysis, compilation and interpretation in the course of preparation of the final thesis.

1.5. Material and Data Acquisition

The following materials have been collected form relevant institutions for the purpose of the present study.

- Topographic maps at a scale of 1:50, 000, namely South Mekele and Kwiha sheets, 1994.
- Aerial photographs four strips 12 in number with a scale of 1:50,000, 1994.
- Mean daily temperature, precipitation, humidity and sunshine hours of different periods.
- Mean monthly wind speed, river discharge measurements and solar radiation measurement.
- Bore hole logs and pumping test data of wells in the study area.
- Chemical analysis data of water samples.

CHAPTER TWO

GENERAL OVERVIEW OF THE STUDY AREA

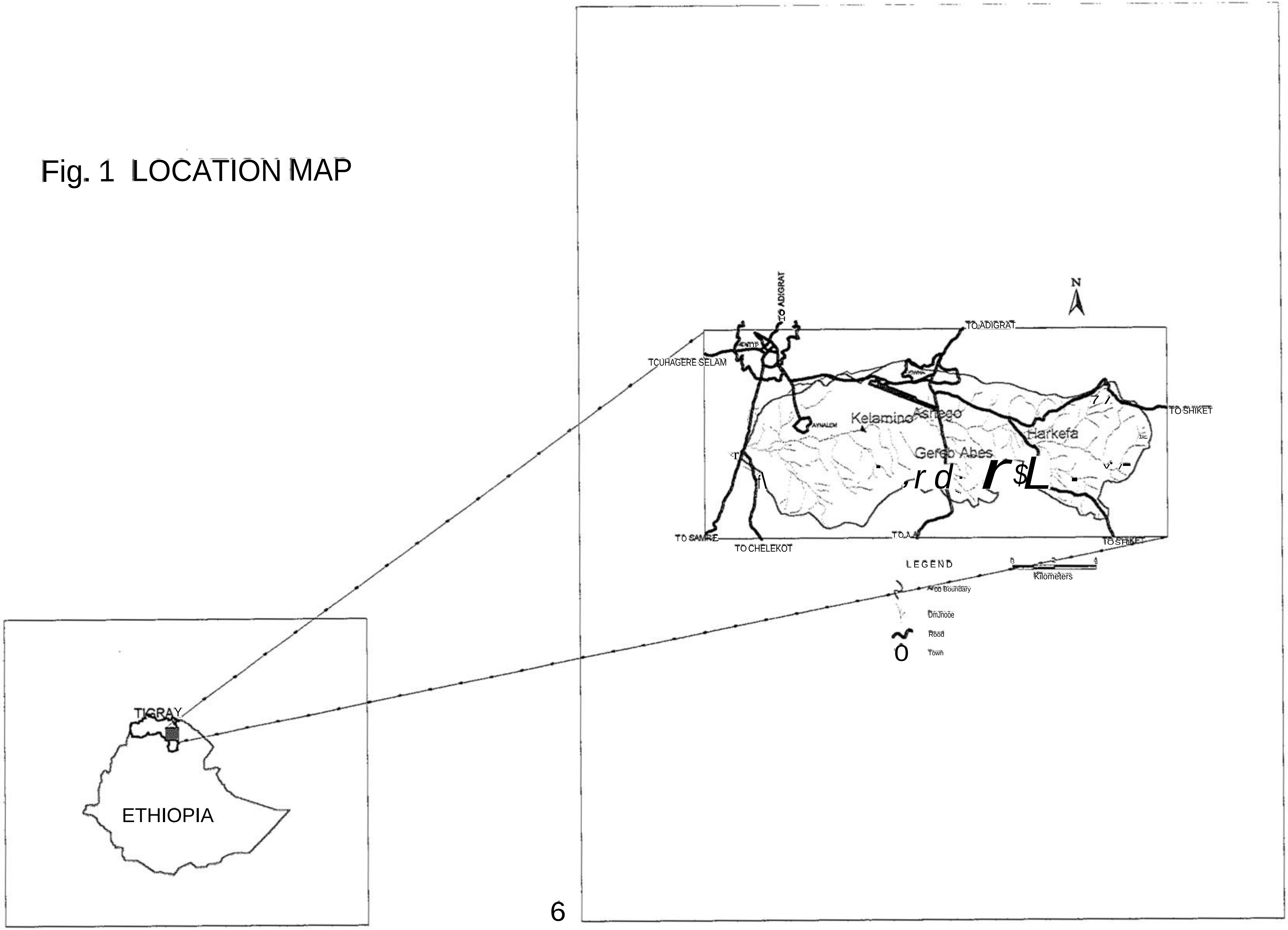
2.1 Location and extent

The Aynalem well field is located about 5 kilometers south of Mekele town, capital of the Tigray National State. It is about 770 kilometers far from Addis Ababa. Latitude $13^{0}24'33''$ to $13^{0}29'49''$ North, and longitude $39°27'30''$ to $39°38'33''$ east bound it. The study area covers about 100 Km^2 (fig. 1).

2.2 Accessibility

The all weather Addis Ababa-Adigrat road crosses the catchment and divides it into almost two equal parts. In the dry seasons most of the area is accessible by a four-wheel drive. But during the wet season, since the area is farmland, accessibility becomes difficult even on the plains. The feeder roads connecting small villages to the main road are also important accesses in the area.

Fig. 1 LOCATION MAP



2.3 Topography

The altitude of the Aynalem catchment varies from 2110 meters above sea level at the mouth of the basin to 2500 meters above sea level at the extreme east. Most of the area falls between 2200 and 2360 meters above sea level. It is bounded by a chain of ridges mainly oriented west northwest on both sides and the central area is characterized a flat lying topography covering about 60% of the total area (fig. 2).

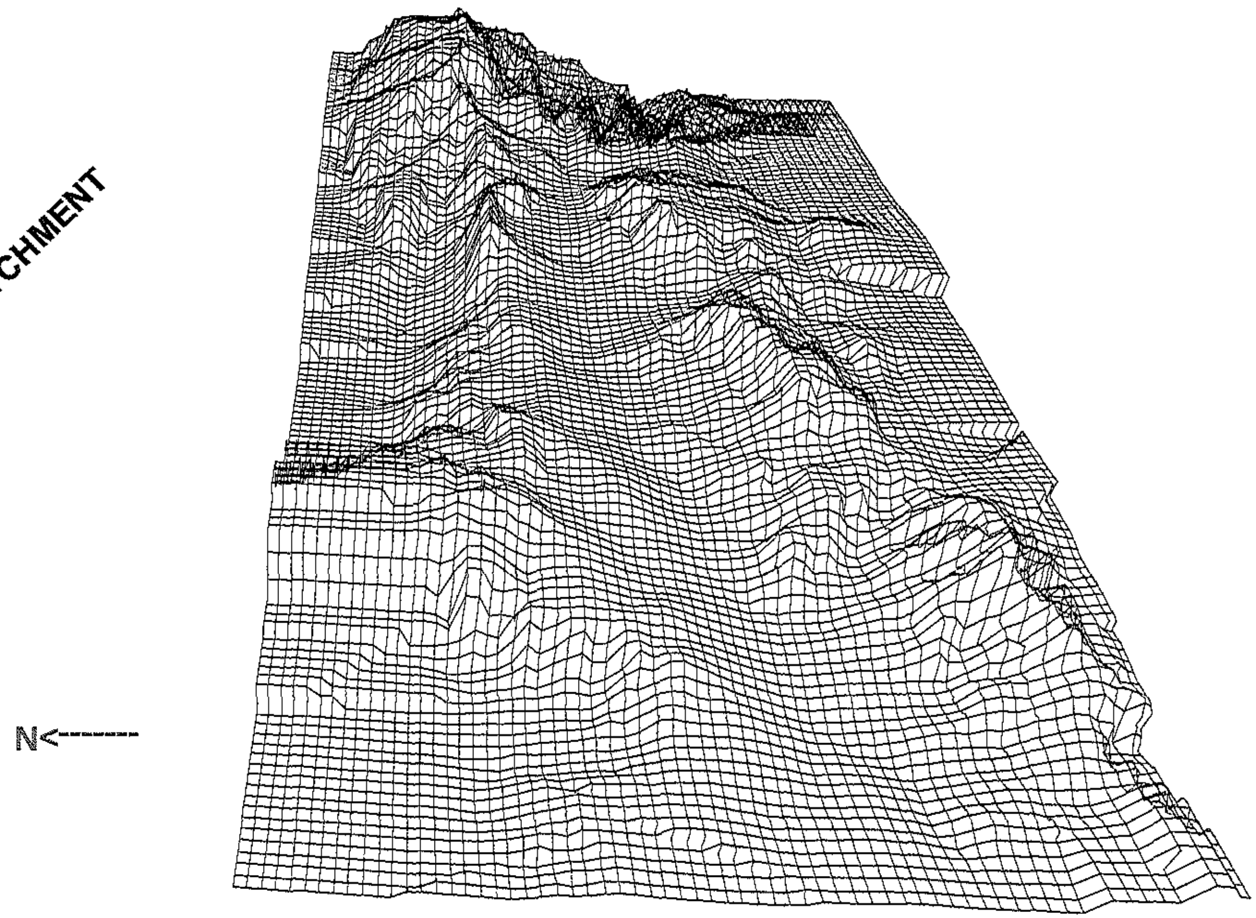
2.4 Drainage

The Aynalem catchment is part of the Tekeze river basin. The Aynalem stream divides the study area almost into two equal halves. This river is strongly controlled by the main fault systems of the area. The Aynalem river flows to the west starting from the east. Seasonal streams feed the main river from both to the south and north. Due to the presence of karstic features, the river disappears in the limestone rocks. The area consists of at least three seepage zones with insignificant initial discharge, but gradually increases to about 8 liters per second downstream.

2.5 Climate

There is one type A meteorological station at the Mekele airport located at the center of the northern boundary of the basin. The area receives an average annual rainfall of 639 mm, about two-third of which falls in July and August. The mean annual temperature is 17°C and the mean annual potential evapotranspiration is 876 mm. The average wind speed is 11 Kilometers per hour.

FIG.2 DIGITAL TERRAIN MODEL OF AYNALEM CATCHMENT



CHAPTER THREE

GEOLOGY

3.1. Introduction

Danelli & Marinelli (1912) and Merla & Minucci (1938) did the first systematic geological mapping of the region. Danelli (1943) proposed the transgression and regression phenomena to explain the sedimentary history of the Horn of Africa, including the Mekele outlier.

The study area is part of the Mekele outlier. This outlier is a near circular area where the Mesozoic sediments have been laid down. The stratigraphy consists of lower sandstone unit (Adigrat Sandstone, Triassic -Middle Jurassic), the Antalo Limestone (Oxfordian-Kimerigian) and the upper sandstone or the Amba Aradom formation, probably early Cretaceous (Bossellini et.al., 1997). A network of dolerite sills and dikes intrudes the sedimentary rocks, in places, has disturbed the original Sedimentary bedding.

According to Levitte (1970), the area is affected by two major fault systems that are normal to each other. They are:

i. A system characterized by normal faults up to 40 kilometers in length, which cut the entire sediment section and trends N25^{0} E. The displacement is very low, and in many cases intruded by dolerite dikes. The same fault trend exists in the basement rocks. It is highly probable that the fault controlled structures existed through out the Mesozoic.

ii. The other fault system is much more prominent, in length and throws. It consists of a parallel series of faults striking N65^{0}W. The most important of these faults is the Mekele fault, which passes about 9 kilometers NE of the Mekele town and forms a long escarpment that is about 65 Kilometers in length. Faulting brought the lower most formation of the Antalo group against its upper most formation, near the town of Mekele, that is a throw of at least 400 meters.

However, Beyth (1970) and Bossellini et. al. (1997), indicated that the Amba Aradom formation is not affected by any of these fault systems and lies with angular unconformity over the underlying Jurassic succession.

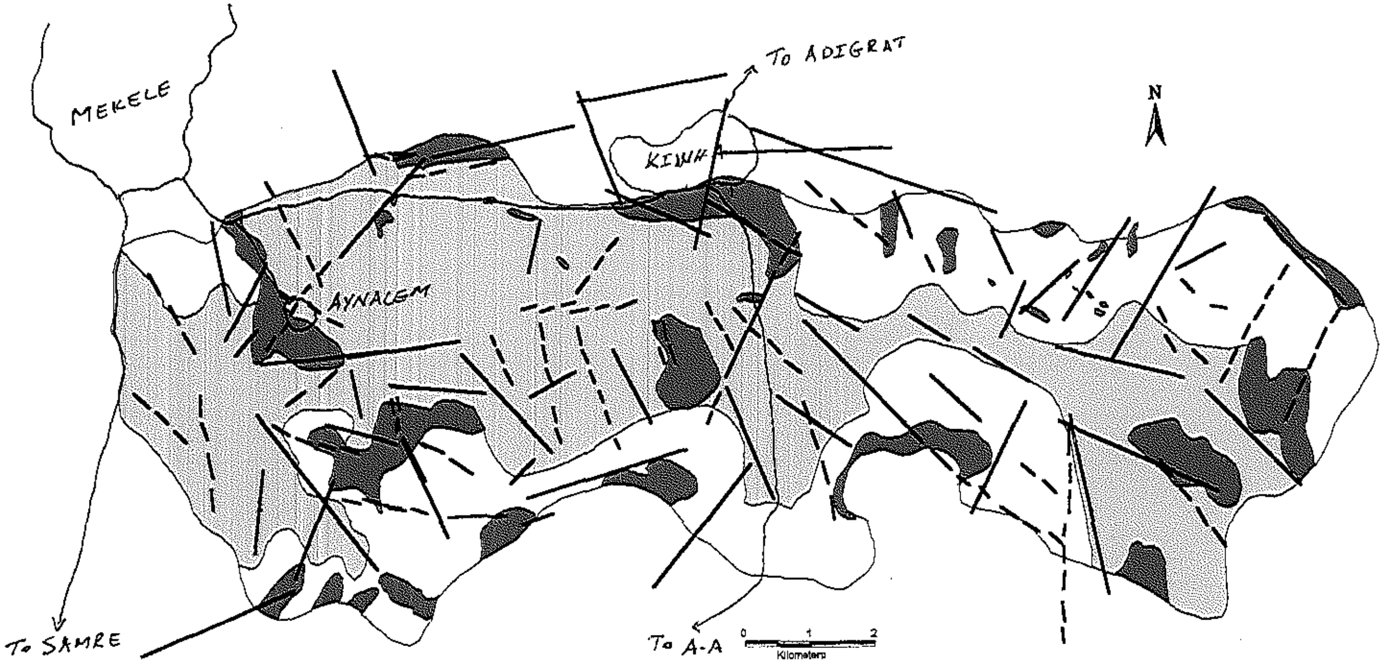
3.2 LOCAL GEOLOGY

Three lithologic units (fig 3) cover the area. These are limestone, shale-marl and limestone intercalation unit, and dolerite.

3.2.1 The limestone unit

It is dark gray to black in color, fine grained, well-bedded crystalline rocks, and in most cases devoid of fossil fauna. It is affected by intense fracturing with no visible inclination. The fracture trend varies from place to place, however it can be generalized as ESE and ENE trending and parallel to the major fault trend of the area. The dominant joints are horizontal. The joint aperture ranges from 2 to 40 cm.

FIG.3 GEOLOGICAL MAP



LEGEND

Observed structure

Inferred structure

LITHOLOGY

- Bedded limestone with swarms of dolerite dikes and sills
- Dolerite
- Limestone, shale & marly limestone intercalation

Dolerite sills and dikes intrude the limestone at different localities. This can be evidenced by the presence of dolerite sills in the lithologic logs of many wells. It seems that this limestone attained its permeability due to the intense fracturing which could be attributed to the outcome of the aforementioned regional tectonics and subsequent intrusion by dolerites.

This unit covers mainly the low laying flat land of the study area, however there are some black limestone exposures with thickness not exceeding 3 meters above dolerites at higher grounds. When this limestone is underlain by dolorite sills it losses its horizontality. This limestone forms small hills with thin soil cover without visible dolerite outcrop adjacent to it.

Under microscope, the limestone is fine grained with some calcite crystals (less than 10%) filling microfractures. It is characterized by long fracture trace through the entire fields of view and discontinuous fracture trends with similar orientation to the main fracture trace and seldom perpendicular to it. No primary porosity and permeability is notified from the thin section.

In more than half of the wells, where sedimentary rocks are encountered, and limestone is the dominant lithology at the base overlying dolerite. In some cases sandstone and marl are intercalated. The limestone has thickness ranging from 5-45 meters while the thickness of the sandstone varies between 10 and 22 meters in the well logs.

3.2.2. Shale, Limestone and Marl Intercalation

Alternating gray and pinkish, highly friable, and laminated Shale overlies the black limestone covering the flat lying land of the study area. Its thickness is variable and gradually increases toward east , but diminishes at places where the limestone unit is exposed. Undulating features manifest the effect of the intrusion of the dolerite in this unit.

Light yellow color thinly bedded fossiliferous limestone is encountered at different localities within this unit. Under microscope this limestone contains quartz crystals , shell moulds which are filled with large calcite crystals and the matrix containing opaque iron minerals with no obvious primary porosity and permeability. In some cases, within the well logs, marl and shale are found in the lower part.

Light green, thinly bedded , strongly fractured and fine grained marl mostly outcrops at a relatively higher altitudes of the area and it is intercalated with limestone and shale.

The different lithologies described above are generally correlated to the Antalo formation described by Levetti (1970) or the Antalo supersequence of Bossellini et.al (1997). However, it is not possible to correlate the units with specific members of the formation, because, it requires more detailed work.

Bossellini et.al. (1997) noticed that the Agula group of the Antalo sequence can be represented into two different areas of sedimentation; one to the southwest and the other to the northeast of the Mekele fault system. The former consists of a well-developed evaporite unit (50 meters thick) along the Mekele - Hagerselam road within the lower part of the Agula succession. Levetti (1970) also indicated the presence of up to 10 cm thick gypsum layers at the upper most section of the Agula shales (type section -Antalo village). But, no evaporite outcrop is traced in the study area.

3.2.3. Dolerites

Ridge forming dolerite dikes and small stocks are common in the study area. The rocks are black, fine to medium grained, hard and in most cases contain phenocrysts of plagioclase crystals. Dolerite sills are also common and is evidenced by the penetration of the dolerite unit in almost all wells drilled in the study area.

Unlike the limestone the fracture patterns are irregular and affected by spheroidal weathering (Plate 1). It outcrops mostly in hills of the catchment. The weathering and fracturing decreases with depth. Weathering products , at places , forms thick soil cover up to 7 meters and 2-6 meters within the lithologic logs of some wells.

Under the microscope, the composition of the dolerite is plagioclase 60%, Pyroxene 35% , opaque iron minerals 2-5% and biotite 0-2%.

The dolerite dikes, if viewed along their long axis , have parallel trend to one of the main structures mentioned above.

3.3.2. Joints

Joints are fractures without displacement. Horizontal joints are the dominant ones in the area and correspond to the bedding planes of the sedimentary succession. Vertical jointing parallel to the main fault trend is also significant. The density of jointing is higher along the contact between the dolerites and other sedimentary units, especially that of the limestone contact is prominent (Plate 3).

CHAPTER FOUR

HYDROMEOROLOGY

4.1. PRECIPITATION

According to Daniel Gamechu (1977), the area is classified as part of the western half of the country, which receives one season rainfall. The available data of the study area includes 1960-1985, 1986-1988, and 1992-1998. The gauging stations were set between Mekele airport , Kiwha & Ilala river from time to time. For practical purpose the records of 1992-1998 are utilized in this work, because they are complete and have relatively complete other corresponding meteorological data. The average rainfall of the area is 639 mm per year. Nearly 66% of the total precipitation falls during the months of July & August and small rain fall in March and April (fig 4).

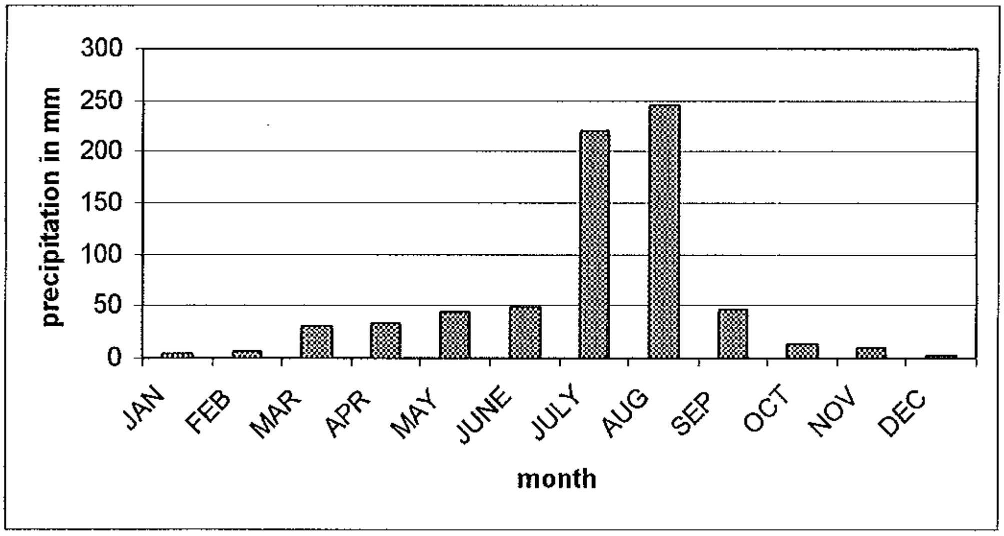
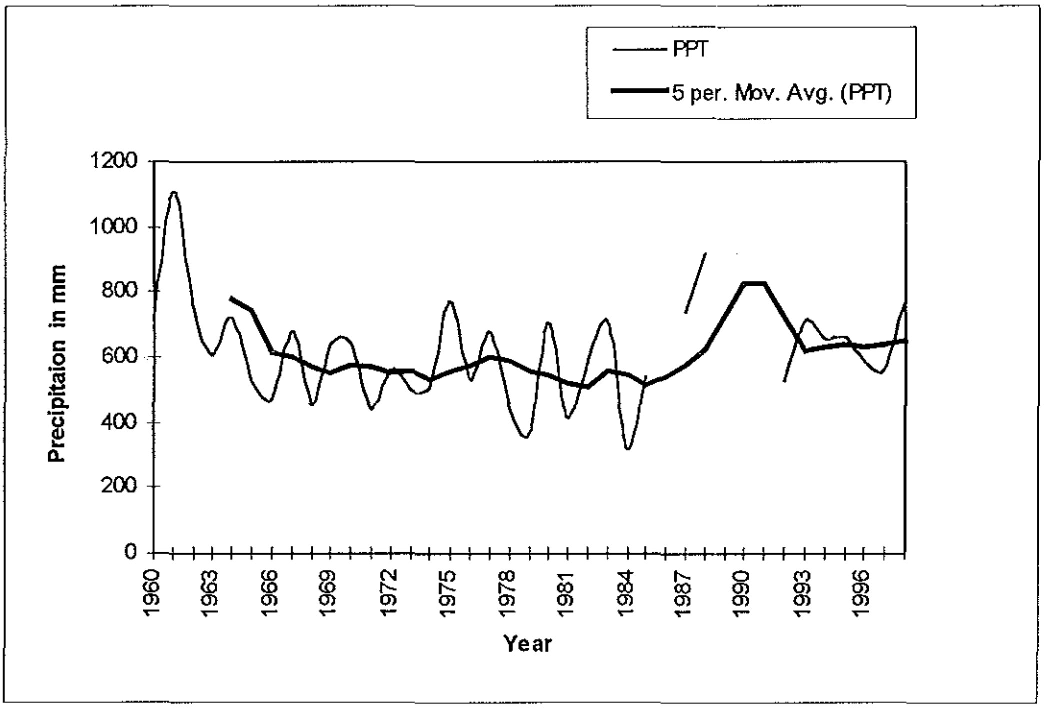


Fig. 4 Monthly rainfall distribution

4.1.1. VARIABILITY OF RAINFALL

The precipitation records since 1960 show high inter-annual variability (appendix 6). The highest rainfall record is observed in 1961 and the lowest in 1984, which corresponds to the greatest drought period which, affected the region. Five years moving average trend shows a continuous decrease in rainfall until the early 1970's and a relatively stable trend after that with a slight trend of rise lately (fig 5).



Fig, 5 Five years moving average .

4.2. EVAPOTRANSPIRATION

4.2.1. POTENTIAL EVAPOTRANSPIRATION

Potential evapotranspiration is defined as the amount of water that would be removed from the land surface by evaporation and transpiration processes if sufficient water were available in the soil to meet the demand. In order to calculate the potential evapotranspiration of the study area various methods have been employed. These are, radiation based methods, temperature based methods and pan evaporation approaches. The objective of calculating the potential evapotranspiration is to extract the actual evapotranspiration values using methods that make use of potential evapotranspiration and to estimate open water evaporation, such as the small ponds, in the study area. The meteorological data required in estimating evapotranspiration are summarized below.

REQUIRED PARAMETERS

a) SOLAR SHORT WAVE RADIATION (K)

The direct short wave and long wave radiation measurements are available for the study area. The incoming solar radiation is measured at the nearby Ilala river for the periods 1974-1975 by Macdonald et.al.,(1975). The record includes ten days average values of each month (appendix 1). The incoming solar radiation values are corrected for albedo allowance and are given in mm/ day. This mass of water is converted to energy by multiplying it by the latent heat of vaporization and the results are given in table 1. It can be observed from the table that the highest values are recorded for the months of March, April, May & October and the lowest values for July & August. This variation could be attributed to the cloud cover variation in the area which has a direct effect on the incoming radiation. The values obtained were used to calculate both the potential and actual evapotranspiration using radiation based and combination approach methods.

b) SOLAR LONG WAVE RADIATION (L)

The recorded long wave radiation data is treated in a similar fashion to that of the short wave radiation before applying it in the evapotranspiration calculations. The lower magnitude of the long wave radiation corresponds to that of the short wave radiation. The result of the long wave radiation is presented in table 1.

c) SENSIBLE HEAT EXCHANGE (H)

It is a none radiant heat transfer which occurs between the ground surface and the air in the form of latent heat when ever there is a difference in vapor pressure between the surface and the overlying air. The upward rate of sensible heat exchange by turbulent transfer is also measured at the same time and the values are given in mm/day. The result shows lowest values in June, July & August having a similar trend with the short wave and long wave radiation. The monthly sensible heat exchange rate is given in table 1.

d) TEMPERATURE (Ta), WIND SPEED (Va), AND RELATIVE HUMIDITY (Wa)

The monthly mean temperature is given in table 1. The maximum and minimum air temperature data are given in appendix 2. The highest temperature is recorded for the months of April, May & June, which coincides with the period when the sun is over head on the area & relatively small cloud cover, is recorded. The lowest temperature is recorded in the months between November and January.

Monthly wind speed measured at two meters above the ground surface at the Mekele airport for the years 1996-1998 is given in appendix 3 . The monthly mean wind speed in m/s is indicated in table1. The data shows that there is high wind in the months of November, December and March to May. The lowest record is that of August.

The average monthly relative humidity varies between 0.45 and 0.75. A 27 years relative humidity records at 0600, 1200 & 1800 hours are given in appendix 4 (a, b, c,) respectively. The highest humidity values correspond to the wettest months of the year (July, August & September), and the lowest to the driest months of April, May & June.

In all cases the available data are averaged and utilized in the calculation of Potential and actual evapotranspiration using the radiation based methods and combination approaches (Dingman, 1994).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
K	338	343	426	440	436	330	312	270	326	399	362	343
L	-134	-114	-125	-132	-137	-76	-59	-49	-76	-133	-145	-135
H	-98	-96	-99	-120	-48	-11	-20	-66	-93	-85	-96	-96
C	9	9	9	11	5	2	3	7	9	8	9	9
va	345	402	399	420	334	220	219	160	197	317	353	367
Wa	0.55	0.52	0.5	0.5	0.4	0.5	0.72	0.75	0.56	0.49	0.52	0.53
Temp	15.4	16.4	17.6	18.6	19.4	19.5	17.2	16.8	17.4	16.7	15.6	14.9
γ*	0.70	0.7	0.701	0.702	0.70	0.70	0.7	0.7	0.7	0.7	0. 7	0.69

Table 1. Summary of meteorological data at Illala and Mekele airport, short wave radiation (K) in cal/cm^2/day, long wave radiation (L) in cal/cm^2/day, sensible heat (H) in cal/cm^2/day, wind speed (va) in m/s, fraction cloud cover (C), temperature in ^{0}C and relative humidity (Wa).

1- RADIATION BASED METHODS

This approach requires data on net radiation, air temperature and pressure. It is a modified Penman's method by Prienstly and Taylor (1972).

The equation is written as:-

$$PET = \frac{\alpha_{PT}\left[s(T_a)\right](K+L+H)}{\rho_W \lambda_v \left[s(T_a)+\gamma\right]}$$

(Equation 1)

***PET* is Potential evapotranspiratiom in cm/day**

The Empirical constants are given as:.

$_{PT}$ *is a constant that depends on the height at which wind speed and air vapor pressure are measured and is equal to 1.26.*

γ *Is psychometric constant, which is a function of temperature and saturation vapor pressure.*

ρ_w *is mass density of water, 1g/cm^3*

λ_v *latent heat of vaporization of water, 590cal/g* *s(Ta) is slope of saturation vapor pressure vs. air temperature (T in °C) and is given by:-*

$$s(T_a) = \frac{25083}{(T+237.3)^2}\exp(\frac{17.3T}{T+237.3})$$

(Equation 2)

2- TEMPERATURE BASED METHODS

a) HAMON METHOD (1963)

$$PET = 0.00138D\left[\rho_V sat(Ta)\right]$$ **(Equation 3)**

*Where **PET** = Potential Evapotranspiration*

D = Day length in hours which is 12 hrs.

$\rho_v sat(Ta)$ = The saturation absolute Humidity at the mean daily temperature in g m^{-3} and is given by

$$\rho_V = \frac{217 * e}{T}$$ **(Equation 4)**

e = Vapor pressure in mb

T = Temperature in Kelvin

b) MALMSTROM METHOD (1969)

$$PET = 0.409 * \left[e_{sat}(Ta)\right.$$ **(Equation 5)**

PET = Potential Evapotranspiration

$e_{sat}(Ta)$ = *Saturated vapor pressure of the atmosphere.*

$$e_{sat}(Ta) = 6.11\exp\left(\frac{173T}{T+237.3}\right) \qquad \textbf{(Equation 6)}$$

c) THORNTHWAITE METHOD (1948)

The Thorthwaite methods requires only temperature data and the equation is given

$$ET_0 = 16*\left(\frac{10t}{I}\right)^a \qquad \textbf{(Equation 7)}$$

ET_0 = *Potential evapotranspiration in mm per month.*

t = *mean monthly temperature in* ^{0} *C*.

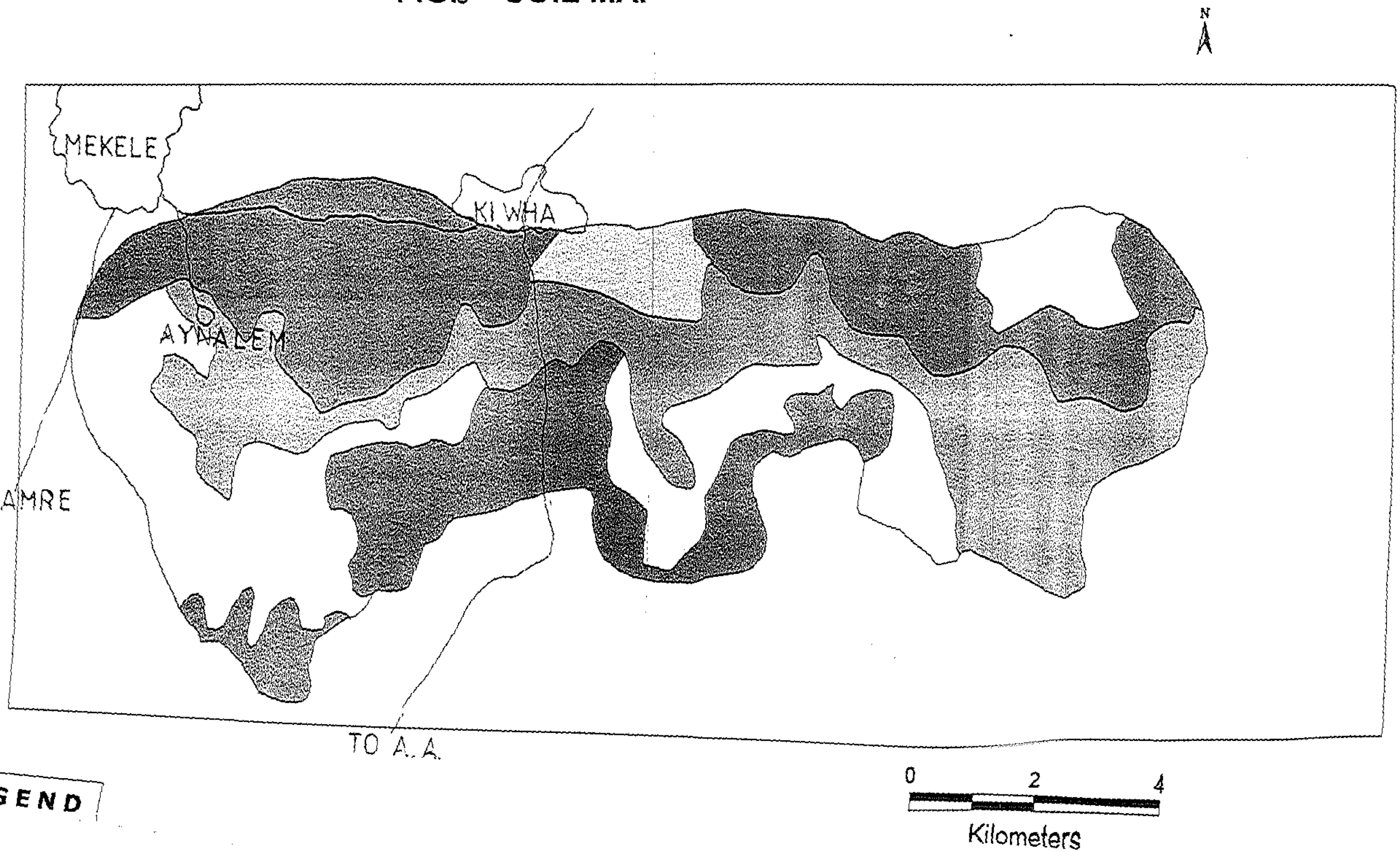
I = *monthly heat index*

I = annual heat index obtained by summing the 12 monthly heat indices,

$$i = \left(\frac{t}{5}\right)^{1.514}$$

$$a = 675*10^{-9}I^3 - 771*10^{-7}I^2 + 1792*10^{-5}I + 0.49239$$

FIG.6 SOIL MAP



LEGEND

Average monthly water balance at Aynalem, Mekele, Northern Ethiopia(1992-1998).													
	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	**DEC**	
Effective precipitation	4.54	4.714	30.45	36.3	39.43	39.25	197.3	212	25.9	18.37	14.5	1.8868	**625**
Potential evapotranspiration(PET)	43	50.1	86.9	79	111	104.5	99.2	65.6	65.1	76.5	48	45.4	**876**
PPT-PET	-38.9	-45.4	-56.49	-43.1	-72	-65.2	98.0	146	-39.2	-58.1	-33	-43.5	
Accumulated potential water loss	-213	-259	-315	-358	-430	-496			-39.2	-97.3	-131	-174	
Soil moisture (Sm)	77.2	58.37	42.63	35.58	28.73	19.15	117.2	206.	184	146.2	124	97.62	
ΔSm	-20	-19	-16	-7	-7	-10	98	89	-22.2	-38.1	-22	-26.55	
Actual Evapotranspiration(AET)	24.9	23.58	46.19	43.4	46.3	48.8	99.2	65.6	48.2	56.5	36.6	28.43	**568**
Deficit (D)	18.5	26.55	40.76	36.08	65.20	55.66	0.00	0.00	17	20.1	11.4	17.0	**308**
Surplus (s)	0	0	0	0	0	0	0	57	0	0	0	0	**57**
Available water for runoff	2	0.891	0	0.223	0.114	0.056	0.028	57	29	14	7	4	**114**
Runoff	0.89	0	0.223	0.1114	0.056	0.028	0.014	29	14	7	4	2	**57**
Detention	0.89	0	0.223	0.1114	0.056	0.028	0.014	29	14	7	4	2	**57**

Table 3. Average monthly water balance at Aynalem, (1992-1998).

Input parameters

The input parameters include - Mean monthly effective precipitation & mean monthly potential evapotranspiration of the considered months and water holding capacity of the soil. Macdonald et.al., (1975) have studied the water holding capacity of soils in the Aynalem and the adjacent catchment (North of the study area) using 300 auger borings for the periods of the dry and wet seasons. The result of their analysis indicate the catchment average soil moisture content is 315 mm and the rooting depth, up to which evapotranspiration is effective, to be 0.70 m.

In this work the soil types of the study area were classified and mapped into four groups (fig.6). Accordingly the area coverage of each soil type is calculated using Integrated Land and Water Information System (ILWIS) program. The root depth of all soil types and the water holding capacity of each soil were adopted from the data of Macdonald et.al., (1975) in running the model.

% Frequency	soil type	field capacity (mm)
3.5	Silty clay	241
43.8	Sand	250
26.3	Clay loam	328
26.4	Clay	347

Table 4. The frequency of occurrence and field capacity of each soil type.

Thus the soil moisture content of each soil and its area coverage has been utilized in determining the weighted average soil moisture content of the total catchment, and is calculated to be 295 mm.

Since the root depth is 0.7 m, the root zone could hold (0.7 * 295) = 206.5 mm of water at field capacity.

	JAN	FEB	MAR	APR	MAY	JUN.	JUL.	AUG	SEP.	OCT	NOV.	DEC	ANNUAL
Radiation	15	15	46.6	30	69	82.5	102	68	54.2	48.5	17.8	16.0	**564.5**
Thornthwait	25	23.8	46.5	44	47	48.8	99	66	48.8	56.4	36.7	28.6	**569.9**

Table 5. Summary of actual evapotranspiration estimation

RESULTS

From table 3 and figure 7, it is possible to see that there is annual surplus of 57 mm. The annual actual evapotranspiration is 570 mm. The soil in the area is under a state of moisture surplus only in the month of August. Macdonald et al. (1975) however measured the excess soil moisture of an adjacent catchment to be 201mm and is in a state of soil moisture surplus in the months of July, August and September. The difference in the measured and the calculated moisture surplus can be accounted to the applicability of the soil water balance of Tornthwaite and Mather (1957) in a fractured and cavernous terrain. The average surplus accounts 9% of the total precipitation. The result shows that the total annual runoff calculated form the model does not fit with the measured river discharge at the gauging station. The model shows an annual runoff amounting 57 mm but the total discharge of the river gauging data shows 36.4 mm of water leaves the catchment as runoff. There is a 19.6 mm difference between the two. This can be attributed to the water loss through limestone cavernous features or through fractures at streambed or there could be groundwater outflow through other conduits.

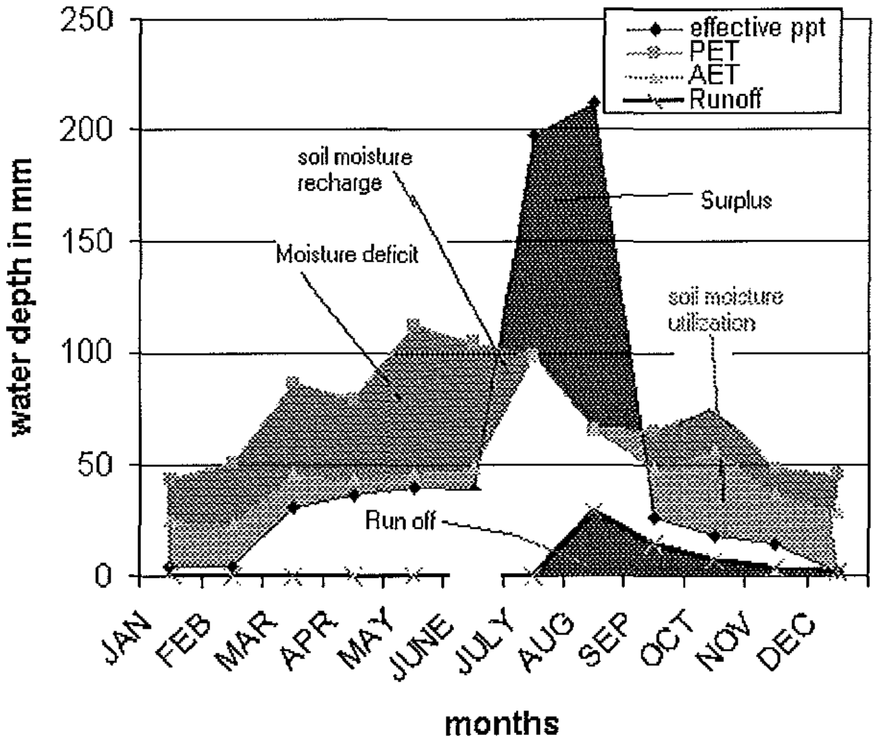


Figure 7.Results of monthly water balance calculation.

4.3. RIVER DISCHARGE ANALYSIS

The river discharge gauging station is located near the Aynalem village, the upstream catchment and covers 69 km^2. However the mapped area is 100 km^2, therefore runoff coefficient is estimated and the recorded data is extrapolated to include the remaining 31 km^2. The monthly discharge values are given in appendix

5. From the monthly average discharge records it can be observed that the volume of water discharged vary annually (fig. 8a) and within the same year (fig.8b). Inter-annual variation goes between 0.7 and 5.7 million m^3 and within the same year varies from 0 to 3.84 million m^3 in 1994. The peaks of discharge correspond to the months of high rainfall usually July & August and declines sharply in September. The rainy season of the area is between mid-June to Mid- September, however there is small rainfall since the month of March, which may contribute to the gradual increase in the river discharge. The discharge following the rainy season could be related to base flow contribution, because the rainfall decreases rapidly.

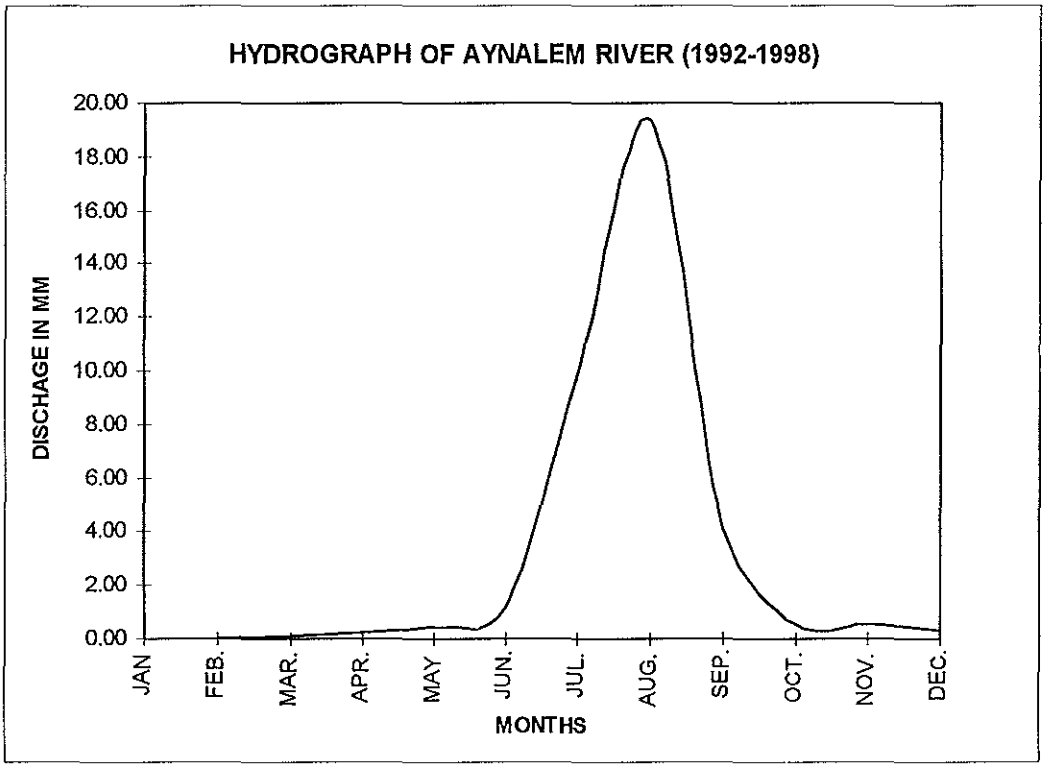


Fig. 8a. Hydrograph of Aynalem river.

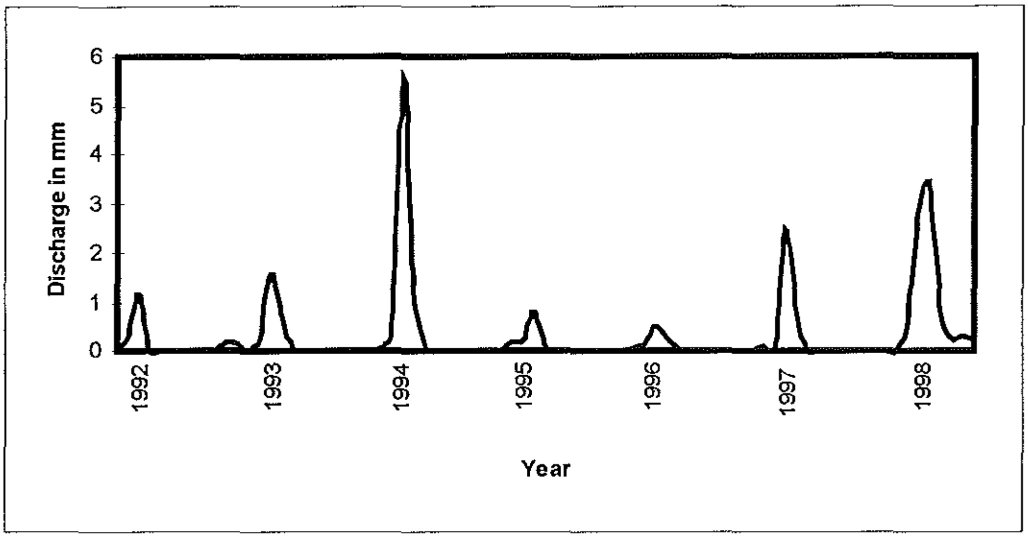


Figure8b. Long-term variation in Aynalem River discharge

4.3.1. BASE FLOW SEPARATION

The total runoff from the catchment area consists of surface runoff, inter flow and base flow. The inter flow is added to the base flow component. Surface runoff comprises the water, which travels over the surface as sheet or channel flow. It is the main component of steam flow during flood and rainstorms. Base flow normally represents the major long term component of the total runoff and is important during long dry periods.

The base flow component of the measured discharge of the Aynalem river starts to rise in the months of March- May and reaches its maximum in the rainy months and eventually declines to zero in December or January. Base flow separation has been made and the result revealed that the proportion of surface runoff to base flow is 4:6, that is of 36.36 mm of runoff 40 % is the surface flow component and remaining 60% is the base flow.

4.3.2. FIELD RIVER DISCHARGE MEASUREMENTS

Field river discharge measurements were done at different places within the Aynalem river using low velocity current meter and floating method. The current meter measures the revolution per second and the values obtained are converted to velocity from a standard chart designed for this specific current meter. The discharge is measured using the relation

$$Q = V * A$$

Where

Q = Discharge in m^3

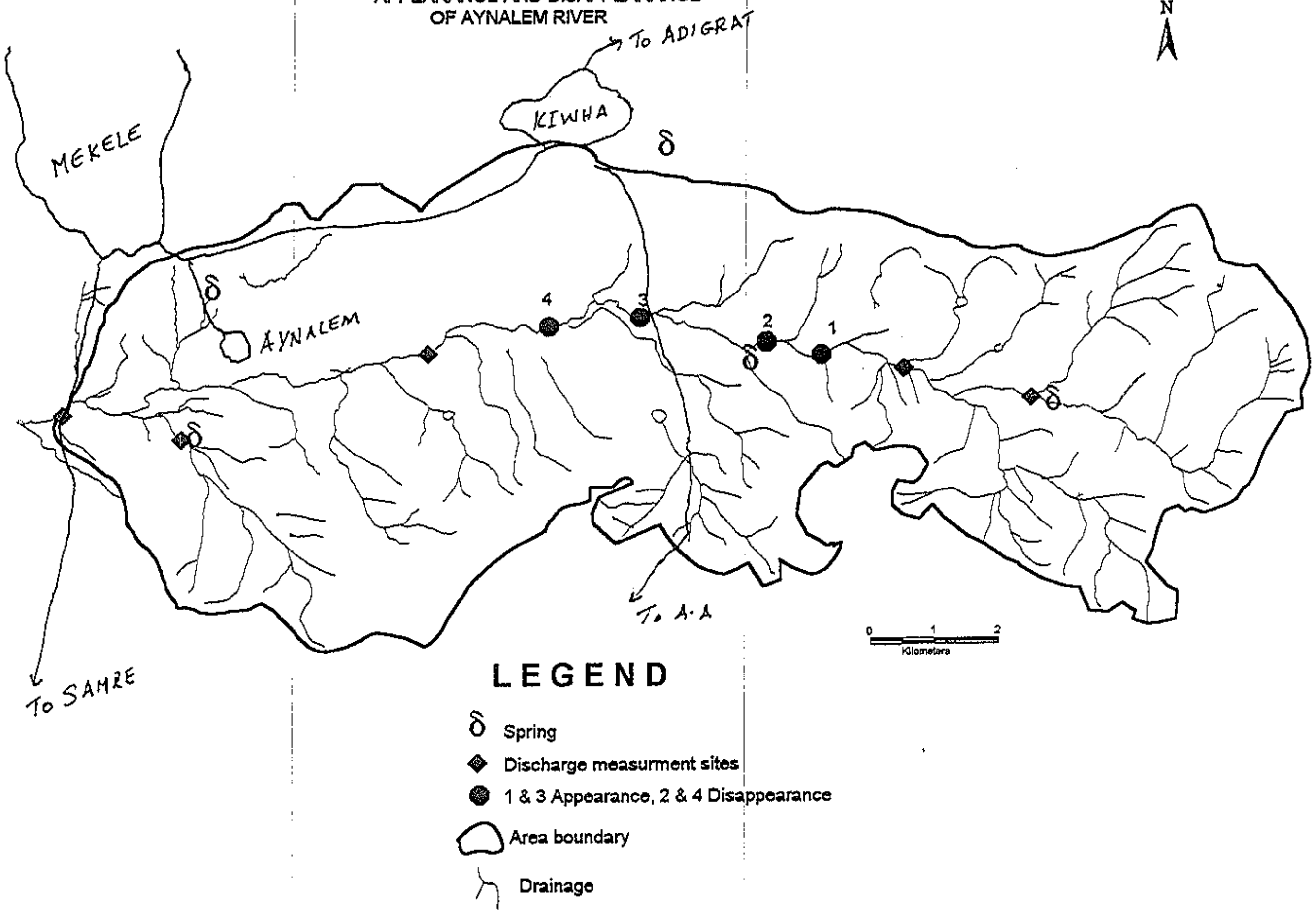
A = Cross-sectional area of the river at which the measurement is taken in m^2

V = Average velocity in m/s

In order to avoid temporal and evaporation effects the measurements were taken within 24 hours. Four measurements were taken and measurement sites are indicated in the figure 9.

The measurement shows that the discharge of the stream varies irregularly along its course. At least two locations at which the river completely loses its discharge have been identified (fig 9). At point 1, the river completely loses its discharge and reappears after 900 m down stream. The same river completely disappears at point 3 and reappears once again after 1500 m. Hydrogeological investigation indicates that the transmisivity and hydraulic conductivity of the wells is highly variable. In addition, many wells show short recovery time after the pumping has stopped to attain their original static water level. Furthermore there are wells that show a decrease in drawdown as pumping time increases (chapter 5). The aforementioned points with the fact that the disappearance points are located on limestone outcrops indicate the presence subsurface channel.

Fig. 9 MAP SHOWING DISCHARGE MEASURMENT SITES
SPRING LOCATIONS and
APPEARANCE AND DISAPPEARANCE
OF AYNALEM RIVER



4.4. WATER BALANCE

Water balance calculations are required to know the amount of water available for ground water recharge and to indicate proper management of groundwater utilization. The water balance calculation is made using the following equation and the components are presented in table 6.

$$P+Q_{in} = R_{off} + AET + E_O + Q_{out} + W$$

Where

P= *average precipitation*

Q_{in} = *groundwater inflow to the catchment*

R_{off}= *surface runoff plus base flow*

AET= *Actual evapotranspiration*

Eo= *Evaporation form open water bodies*

Q_{out}= *groundwater outflow form the catchment*

W= *withdrawal for water supply*

The estimation of the different hydrologic parameters involves different important considerations and assumptions. Water balance is done for the data of the years 1992-1998 because the discharge measurements and relatively proper recording of precipitation is available for this period.

The amount of AET over the entire catchment has been estimated in the previous section using Penman and monthly water balance approach (table 5). The monthly water balance result, which is 570 mm, is used in the calculation. The amount of runoff that leaves the catchment is measured to be 36.4 mm annually. The open water evaporation (E_o) of the ponds in the catchment is estimated using the Penman method for open water estimation and is 2.2 mm annually. The data of groundwater withdrawal from the wells in the well field, supplying the Mekele town, is obtained from the Mekele Water Supply Department and is equal to 11. 2 mm.

Groundwater outflow is obtained form the calculations using Darcy's law, which is given as:

$$Q_{out} = K * A * \frac{\partial h}{\partial x}$$

Q_{out} = ground water outflow

K = Hydraulic conductivity in m/s

dh = Change in head

dx = Length between the two reference points

*A = Cross sectional area of the zone of groundwater outflow (Width * depth)*

The presence of groundwater outflow from the catchment is manifested by the presence of the Kwiha springs (Plate 8) in the adjacent Dolo catchment. The surface catchment of these springs is very small to continuously feed these perennial springs. On the other hand, the fault lines connecting these adjacent catchments and the difference in elevation between the Aynalem and Dolo rivers favors groundwater outflow from the Aynalem catchment.

The average hydraulic conductivity values of the wells near the groundwater outflow zone (PB8 and PB9) are used in the calculation. The hydraulic head is estimated form the elevation measurements near the outflow zone. The area is calculated form the average aquifer thickness form the wells and the average width of the outflow zone. The result of the Darcy's equation shows an annual groundwater outflow amounting 56.8mm.

Therefore the groundwater inflow is (Q_{in}) is left as a residual and calculated form the above equation. The annual amount of groundwater inflow is equal to 37.6 mm.

On the other hand the groundwater inflow to the catchment has also been calculated based on similar assumptions considered in the groundwater out flow. The presence and delineation of groundwater inflow zone is evidenced by the presence of small swampy area with continuous seepage near the southern water divide of the catchment. The annual groundwater inflow using Darcy's equation is estimated to be 37.4 mm. A striking point here is that the results obtained form the independent methods of Darcy's law and the water budget approach come out with the same values. This justifies the validity of the assumptions and the result.

P	**Q_{in}**	**AET**	**Q_{out}**	**E_o**	**W**
639	**37.56**	**570**	**56.76**	**2.2**	**11.24**

TABLE 6. Water budget component

Based on the transmissivity and hydraulic conductivity values a hydrogeological map of the area has been constructed (fig. 13). A detailed description of the hydrogeological characteristics of the different lithologies is discussed below.

5.1.1. THE LIMESTONE UNIT

Two types of limestones are distinguished in the area, black and fossiliferous limestones. The primary porosity and permeability of the black limestone is very low as observed from thin section analysis. However, secondary porosity and permeability is evidenced by the presence of intense fracturing. This limestone is one of the main aquifer units, having the highest hydraulic conductivity (k) values ranging from 29.2m / day to 74.4m / day. The highest permeability value at the contact between limestone and dolerite could be attributed to intense fracturing during the emplacement of dolerite. The degree of fracturing of the limestone can also be influenced by the thermal effect of the dolerite dike and sills. The zone cooked by the magma may show high degree of fracturing due to the associated change in its physical property (such as change in grain size, mineralogy, and competence etc.).

The fossiliferous limestone intercalated with shale and marl show moderate primary porosity under thin section analysis. The secondary permeability however may be the result of fracturing during the swelling and shrinking of the shale that is intercalated in the formation. The effect of the dolerite dikes and sills (as indicated in the above paragraph) can also contribute to the formation of the secondary permeability & porosity.

5.1.2 Sandstone

The sandstone layer in the shale, marl and limestone intercalation unit has a thickness of 2-3 m. In addition to its primary porosity and permeability observed in the thin section, it has secondary permeability due to fracturing. The cementation by carbonate minerals, which is observed under microscope, however reduced both primary and secondary porosities. This layer is also a local permeable unit in the northwestern part of the area, (in well PB 11). This well has one of the highest hydraulic conductivity values i.e. 74.4 m/day.

5.1.3. DOLERITE

This unit has virtually no primary porosity and permeability. It acts as local confining layer when it is massive and unfractured. Vernier (1985) stated that there could be a certain amount of water circulation within the fractured dolerite, due to its remarkable thickness. This unit has low hydraulic conductivity in wells in which the dolerite is the main or the only aquifer unit. The hydraulic conductivity values ranges from 0.02-1 m /day. However the unit can be locally a good aquifer when it is fractured.

5.1.4. SHALE AND MARL

As described in chapter two, they are very fissile and friable. They are intruded by the dolerite intrusions. Levitte (1970) indicated that the most preferred horizon for dolerite intrusion is the upper unit of the Agula formation, which is soft and has a low over burden than similarly soft formations that are exposed at deeper levels. Therefore the intrusion of dolerite into this unit resulted in the development of fractures, which increases the porosity and permeability of the unit which would have been impermeable. Wells containing shale as a significant unit have hydraulic conductivity 1-1.4m/day. Therefore due to the development of fractures the unit can be considered as an aquitard rather than as aquiclude.

5.2. GROUNDWATER RECHARGE AND DISCHARGE CONDITIONS

5.2.1. RECHARGE

Recharge is defined as that portion of infiltrating water that reaches the saturated zone. Geologic structures and type of soils and rocks control recharge. The geologic structures such as primary porosity in rocks, fractures, cavernous features in limestone, bedding planes in sedimentary rocks, and tectonic structures such as faults & joints, and weathering residue of rocks facilitate the ease of water percolation to the groundwater and are good horizontal pathways for groundwater flow.

5.2.2. SOURCES OF RECHARGE

5.2.2.1 Recharge pathways

In the studied area all groundwater circulation pathways indicated above have been identified. The presence of cavernous features, weathering residue and soil, faults and joints of varying orientation, and bedding planes between lithologies, are believed to control the groundwater recharge and circulation.

Some previous works emphasized the importance of faults extending to deeper levels as the main sources of recharge for deeper aquifers. According to Vernier (1985), the dolerite sills and dikes out cropping in the area, are intensively affected by fracture and fault discontinuities together with important vertical and horizontal displacement. And the occurrences of these tectonic structures at depth could suggest the existence of potential lines of water percolation towards the deeper layers. In addition to controlling percolation of water to deeper layers, the faults are believed to play a role in acting as a pathway for groundwater inflow and outflow to and from the Aynalem catchment

5.2.2.2. Recharge Mechanism

In order understand the different mechanisms of groundwater recharge, water budget analysis using Thornthwait-Mather soil moisture balance method have been carried out (chapter 4). The result of water budget analysis and additional field evidences suggest the presence of mainly four different ways of groundwater recharge with variable degree of importance. These are rainwater infiltration through soils, channel loss, groundwater inflow from adjacent catchment and seepage form ponds and reservoirs in the area. Of these different ways rainwater infiltration through soil is believed to be the most important one.

a) RAIN WATER INFILTRATION

The result of the soil moisture balance of Thornthwait and Mather method shows that, of the total (surplus) 114 mm available water for runoff, half of it, that is 57 mm of water is assumed to be detained in the soil and eventually recharge the groundwater. The remaining 57 mm is converted to surface runoff. The result indicates that the vertical recharge from the soils is the most important component of the direct recharge of the groundwater. Though the amount of surplus is small as compared to the measured value by Macdonald et.al. (1975) it remains the most important component of recharge.

b) CHANNEL LOSS

The river discharge measurement carried out for the Aynalem river since 1992 shows that the annual average discharge is 36.4 mm.. As discussed in section 4.3.1, the base flow accounts for 60% (22 mm) of the discharge while the remaining 40% (14.4 mm) has its source form the overland flow.

Comparison between the calculated 57 mm runoff and the overland flow component of the measured runoff 14.4 mm of the Aynalem river shows that there is 43.4 mm difference. Therefore 43.4 mm of water is lost from the channel and ultimately recharges the groundwater. Field evidences support this hypothesis. The presence of cavernous features, the location of the rivers on fault zones and disappearance of the river water at various locations suggest the loss of the river water into the underlying groundwater body. Previous soil water balance study by Macdonald et.al., (1975) on the adjacent Dollo river catchment (a catchment with fairly similar geology and soil cover) also indicated the importance of channel loss in groundwater recharge.

c) SEEPAGE FROM RESERVOIRS

There are nine artificial ponds of variable size within the catchment (figure 10). Water level observation of the reservoirs shows that they are characterized by considerably high amount of water loss after few months of the rainy season. At least 2 ponds (Dendera and Mokoro) show complete loss of their water reserve at the end of October or November of each year, that is after 3 months of the main rainy season (plates 4 & 5). Permanent ponds in the area also loose significant amount of their water after the rainy season. The Adi- Akoro pond is a good example, it attains its full capacity in August and shows a decline of 10 m in the month of November each year (plates 6(January) & 7(April 2000)).

In order to understand the hydrology of the ponds a preliminary water budget studies has been carried on some of the ponds. The balance between open water evaporation loss, percolation loss and the total amount of water lost form the ponds have been conducted on the Adi-Akoro pond. The data of water level of the pond has been obtained from Sustainable Agriculture and Environmental Rehabilitation of Tigray (SAERT), 1998. The result of the analysis is indicated in table 7.

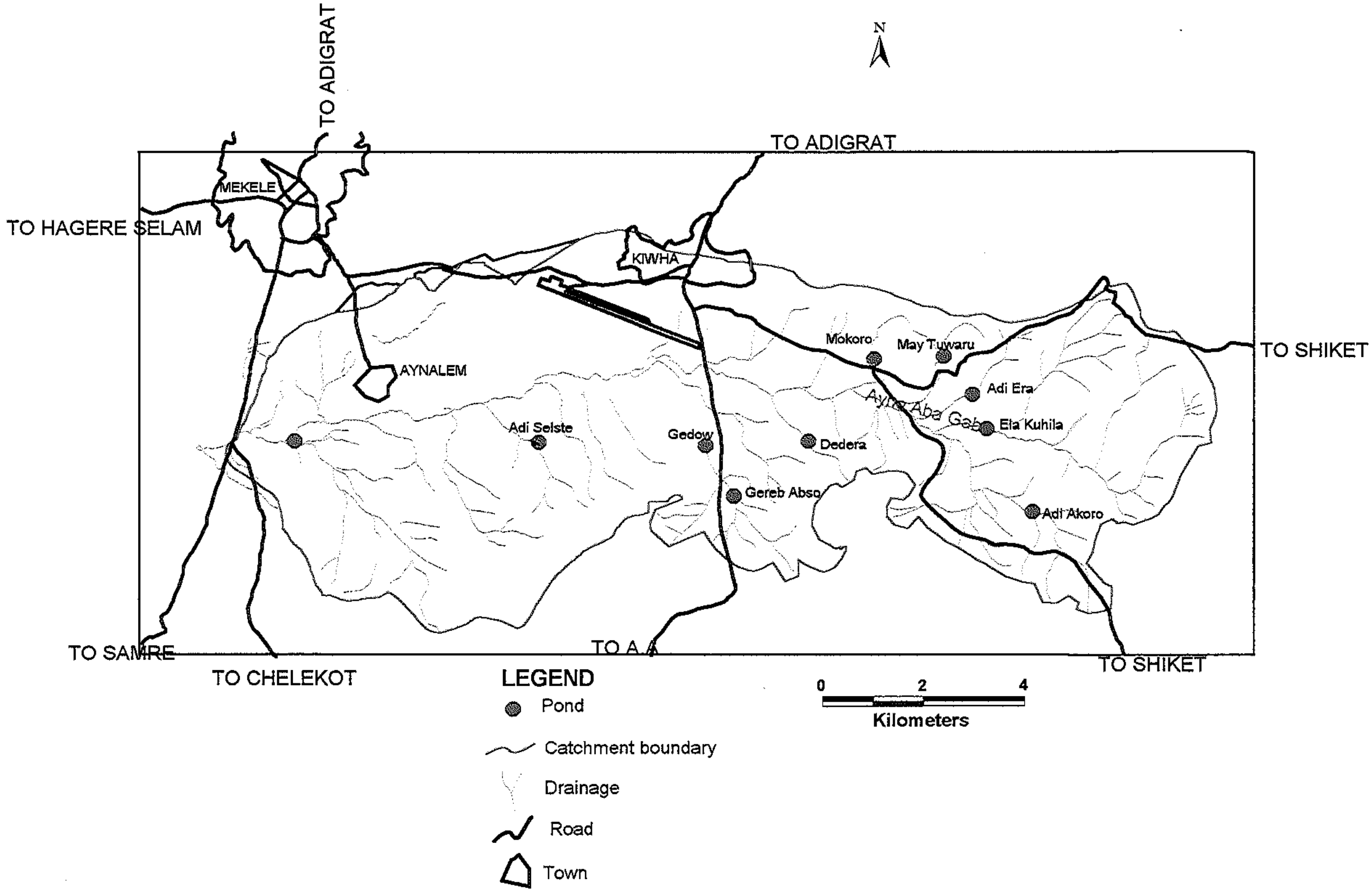
Time of measurement	Capacity at initial reading	Capacity at final reading	Evaporation loss	Seepage	Total loss
Early Sep. to 26-9-98	345,000	331,421	1,527	12,052	13,579
Early Oct. to Early Nov. 98	331,421	231,095	9,936	90,390	100326
Early Nov. to Early Dec. 98	231,095	134,405	6,300	90,390	96,690
Early Dec. Early Jan . 98	134,405	37,605-1050 *	6,400	90,390	96,790
Early Jan . to Early Feb. 98	36,555	15,885-3,900*	2,592	18,078	20,670
Early Feb. 98	11,985	7,532-1,335*	3,013	1,440	4,453
Late Feb. 98	6,197**				

Table 7. Variation in water reserve of the Adi Akoro pond in m^3
* The amount of water used for irrigation in each period, ** Dead storage i.e. can not be utilized for irrigation.

The result of the analysis shows that over 90 percent of water loss from the pond is due to percolation and the remaining less than 10% is due to evaporation.

One striking point obtained from the result is that the total seepage loss (315, 000 m^3) from the Adi-Akoro pond is by far greater than the aggregate evaporation loss (278,000 m^3) from the nine ponds in the area utilizing the Penman combination equation for open water evaporation.

FIG. 10 AYNALEM PONDS LOCATION MAP



All the ponds are built along fault lines of the main fault systems and on cavernous limestone. Therefore the possible pathway for water loss from the ponds could be the fault lines or along the cavernous features or both. The water lost form the ponds is believed to contribute significant amount of recharge to the groundwater system indicating that the ponds are constructed above the static groundwater level.

d) REGIONAL RECHARGE

Apart from the recharge within the catchment, it is believed that groundwater inflow from adjacent catchments play a role as a source of groundwater recharge. The presence of springs near the southeastern water divide (Ashegoda village) suggests the possibility of such a source. The groundwater inflow from adjacent catchment is controlled by geologic structures. Beyth and Shachnai,(1970) stated the presence of asymmetric syncline between Mekele and Chelekwot faults. The axis of the syncline being the Ilala river, North of the study area. They also indicated that the Mekele town , including the Aynalem catchment, are located on the longer limbs of this fold. This structure on one hand may provide a suitable geometry for the presence of leaky and sub artesian system and on the other hand it acts as a suitable geometry through which groundwater is transferred from adjacent catchments. Water budget study for the Aynalem catchment also indicates the presence of 37.4 mm of groundwater inflow from the surrounding catchments.

5.2.3. DISCHARGE

Discharge areas are characterized either by springs, which have measurable flow, or seepage zones where the flow is diffused. The discharge areas are along stream banks, mainly on the banks of the Aynalem river. Lithology and structure control the discharge zones. On the shale-marl intercalation unit, temporary marshes are observed. Most of the marshes are located in the flat laying parts of the shale-marl intercalation unit. Seepage from the shale or the contact between shale and limestone may result in the formation of the abundant marshes. A regional groundwater study by Tesfaye Chernet (1993) also shows that the Agula Shale is characterized by a large number of springs which emerges at the contact between limestone beds with shale or dolerite (Tesfaye Chernet, 1993).

5.3. WELLS

There are 27 wells in the Aynalem wellfield which are named as TW (test well), PB (pumping well), E (all wells except TW and PB), Lesperance, Airport well etc., out of which only one well is unproductive. Step drawdown, constant pumping and recovery test data of 17 wells are available from the Water Wells Drilling Enterprise and the Ministry of Water Resources Development. The data were utilized to analyze the storativity and permeability of aquifers.

Most of the wells were drilled near the main fault systems of the area and well sites in the early 1970 were selected from geophysical data run along fault traces oriented NE-SW which are observable from aerial photographs. The subsequent well site locations appear to follow the same trend except those wells drilled in 1998. On the other hand, most of the lately drilled wells are located along another fault system running E-W and some of these wells assume the same trend of the early once. Generally, the distribution of the well indicates high density along the northwestern part of the catchment and the right bank of the Aynalem river. At least there are three wells every two square kilometers in this well field, which is extremely dense.

This has an adverse effect on the future sustainable groundwater utilization of the aquifer potential, because the radius of influence of many wells could coincides. This will increase the drawdown of the aquifer significantly. The radius of influence is the distance between the pumping well center and the point in the aquifer where the drawdown is equal to zero or the radius of influence could be interpreted as a distance beyond which the drawdown in negligible.

One important point to note is that this aggregation of wells in one side of the catchment (fig. 14) created difficulty of estimating the hydraulic parameters of the aquifer using pumping test data for the other half of the catchment. Therefore, data from the northwestern part is extrapolated for the whole catchment.

5.3.1 AQUIFER PROPERTIES

5.3.1.1. TRANSMISSIVITY AND HYDRAULIC CONDUCTIVITY

In analyzing the aquifer parameters such as transmissivity, storativity and hydraulic conductivity, a problem of obtaining accurate hydrogeological field data with carefully monitored pumping test was encountered. In almost all cases the recovery test data were not complete since it was interrupted before complete recovery of the wells was attained. This condition created a difficulty in the analysis of recovery test data.

Aquitest for Windows computer program developed by Roehrich has been used for analysis of aquifer properties. First, it was necessary to define the aquifer system before selecting the method to determine aquifer parameters.

The static water level data shows it is above the level at which the groundwater was struck during drilling of the wells (table 8). This is sufficient evidence to consider the aquifer as a confined system. However, the area is affected by intense fracturing. The evidence obtained from soil moisture balance calculation and measurement indicate there is vertical groundwater percolation through the soils and rocks. The aquifer system is thus considered as leaky aquifer. Therefore, Hantush (1960) for leaky aquifer curve solution was utilized. The curves resulted from one well method also show a strong fit to the type curve of a leaky (semi-confined) aquifer system.

The program requires inputs of aquifer thickness, well and casing radius, pumping rate, depth and distance from pumping well. In many wells the length of the screen corresponds the thickness. In a single well method the radius of the borehole was used as distance to observation well. The pumping wells were sometimes used as observation wells when a nearby well is pumped and in such cases the distance between them was taken. Porous media and fully penetrating well is assumed in all the analysis.

The result shows that the transimissivity values range between 1-2630 m^2 / day, the hydraulic conductivities 0.02-80.5 m / day and the storativity $3.3x10^{-8}$ $-1.5x10^{3}$ (appendix 10).

WELL LABEL	STATIC WATER LEVEL (M)	WATER STRUCK (M)	LITHOLOGY
PB1	11.2	21	sst+dolerite
PB2	31.3	109	dolerite
PB3	20.55	80*	lst + dolerite
PB4	15.15	-	-
PB5	13.33	-	dolerite
PB6	19.73	-	lst+dolerite
PB7	8.01	20	lst+doleite
PB8	19.31	38	lst+gravel
PB9	16.26	58	lst+sst
PB11	9.8	62	sst
PB12	14.97	28	lst+dolerite
AIRPORT-1	22.45	70	lst+dolerite
AIRPORT-2	8.65	15	lst+dolerite
TW-3	19.51	56	-
TW-4	16.05	81	dolerite
TW-5	17.56	72	dolerite+sst+lst
LESPERANCE	10	-	dolerite+lst+shale
MTW-1	6.6	-	gravel+shale+lst

TABLE 8 Summary of the static water level & water struck points. * the water struck point is obtained from geophysical well log. Lst =limestone, sst= sandstone

5.3.1.2. PUMPING AND RECOVERY TESTS

a) Time- drawdwon curves

The drawdown of all wells in real aquifers will extend until either the well is supplied by vertical recharge or a hydrologeologic barrier is encountered. These could be the source of recharge, such as a stream or lake, or the edge of the aquifer (Feter, 1988).

The wells in the study area can be grouped in to three based on the pattern of the time drawdown plots.

i). Wells with sharp initial increase in drawdown and short recovery time.

Well PB5, shows the highest drawdown as compared to other wells in the area. It shows a total drawdown of 74 meters in 1000 minutes. However the drawdown starts to decline as the duration of pumping increases (fig 11a PB5).The recovery test data show that a rapid recovery of the well after the pumping has stopped (fig.11a PB5 recovery).

The draw down curve of well PB5 could be explained by the proximity of the well to the Aynalem river. Direct supply of water from the Aynalem river to the well due to the artificial decline in head might have resulted in a curve that shows a reduced draw down as pumping time increases. The other well with a similar time drawdown and time recovery curves is well PB9. The time required for well PB9 to recover the water level is by far smaller than the time required to give rise to total drawdown of 30 meters.(fig.11a PB9 and PB9 recovery)

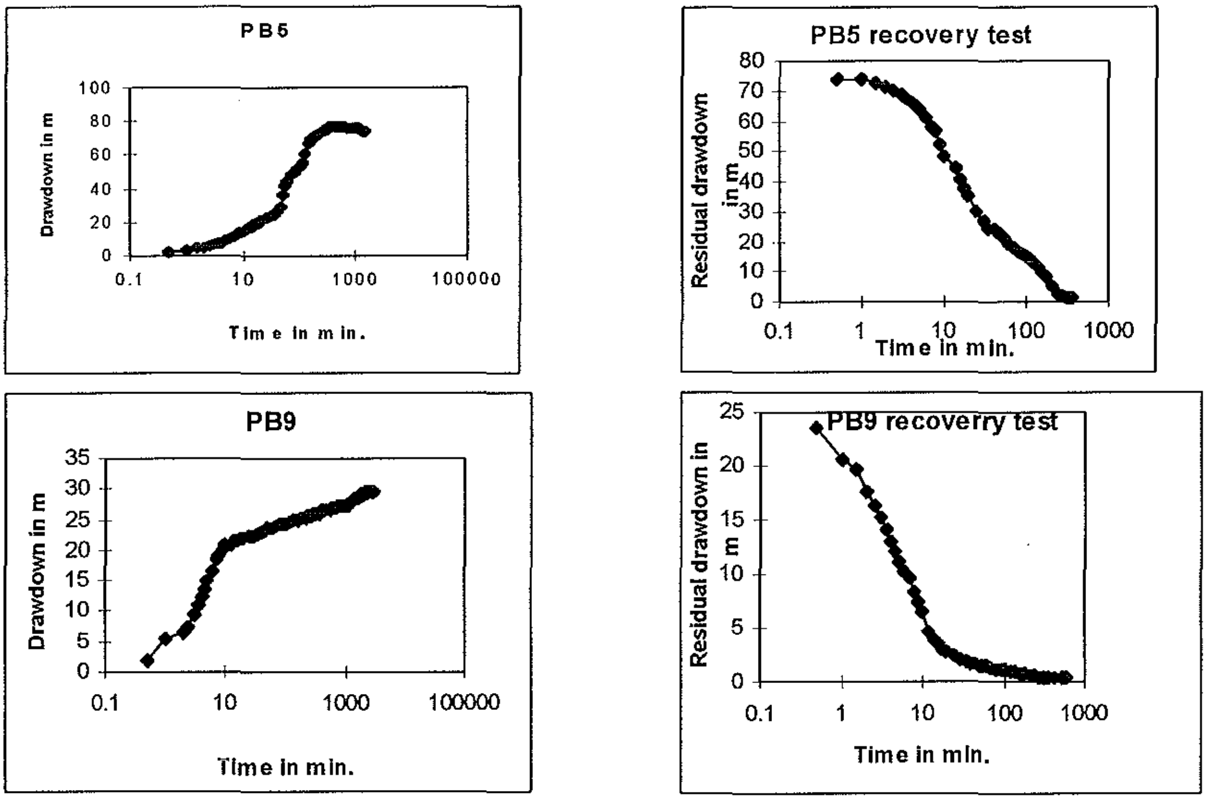


Figure 11a. Time drawdown plots.

ii) Wells with a sharp drawdown as pumping time increases

The time drawdown plots show almost no influence at the initial stage. As the pumping time increases the drowdawn sharply increases (fig. 11b). The wells that show such type of curves are well TW 4, TW5, E2, and TW3 . This could be due to the presence of impermeable boundary, at least locally.

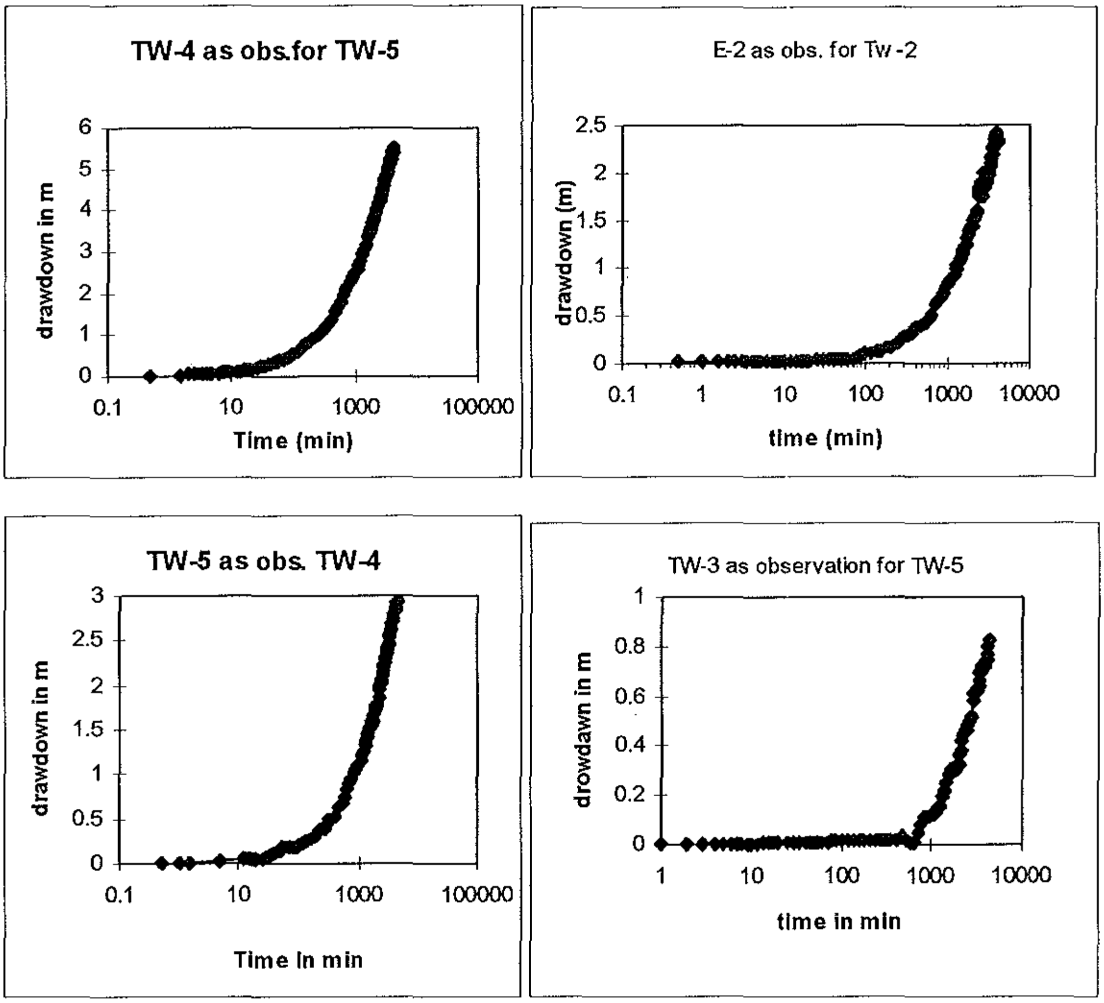


Figure 11b. Time drawdown graphs

iii. Wells showing aquifer homogeneity.

It can be observed for the above figure that when well TW 4 is pumped using TW 5 as an observation well and vise versa the two curves show virtually similar pattern. The hydraulic conductivity and transmisivity show a value which differ by less than 1%. This observation may lead to the conclusion that the hydrogeologic media between the to wells is homogenous. Although it is not possible to draw the same conclusion to the whole aquifer it is evident that the media between the two wells is quite similar.

b) FIELD CURVES

Most of curves of the analysis using single well method fit the Huntush type curves (fig. 12). However, the curves of some observation wells do not fit the type curves. This discrepancy could result from:

- The continuous pumping of the other wells in the area while the pumping test is conducted. This brings about irregularities in the drawdown of both the pumping and observation wells. The drowdawn in the observation well is influenced by the pumping well under consideration and the other wells.
- The presence of cavernous features in the limestone aquifer and the intense fracturing of all the units could contribute to the sudden increase in the amount of water entering wells. Well TW-3 as an observation well during pumping of TW-5 (appendix 9) is an example of such a condition.
- There may be error during data recording and compilation.

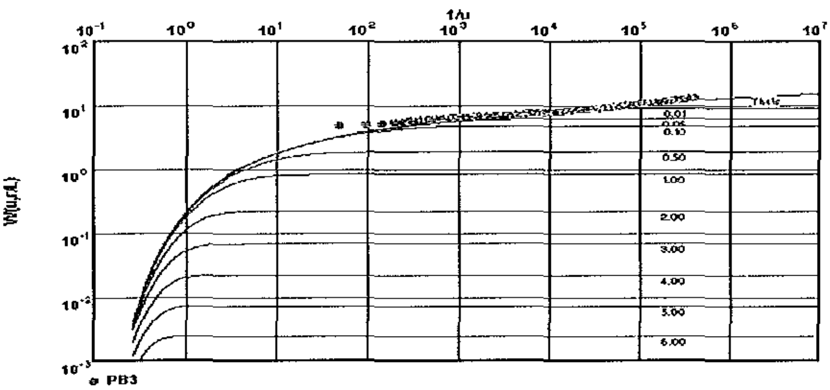
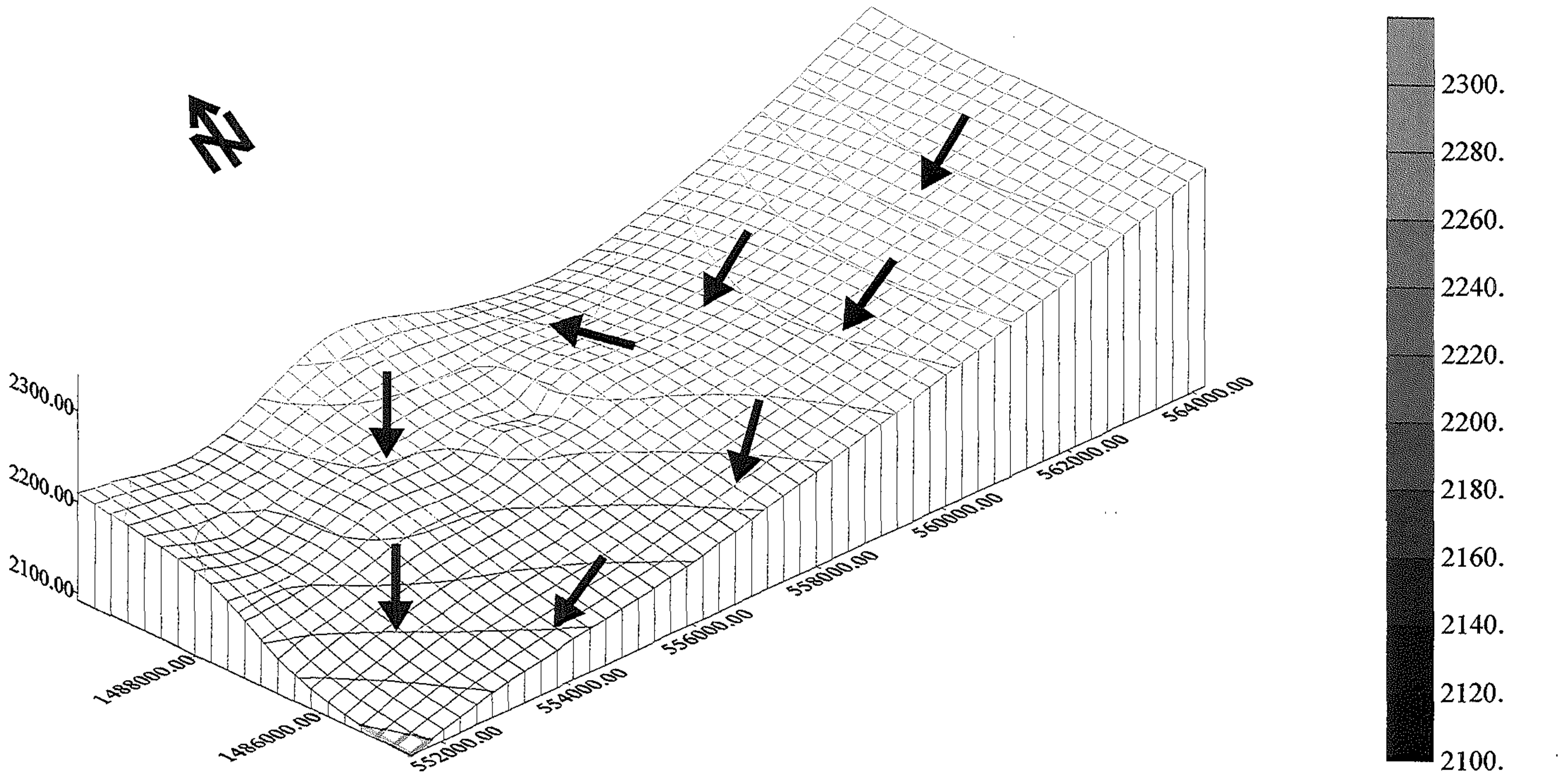


Fig.12. Field curve of well PB3 .

fig. 13 piezometric map



5.5 WATER DEMAND

The data obtained form the Mekele water supply department indicate that water consumption of the town is 35.5 litters per second (lps). Out of this 61% (25 lps) is supplied from the Aynalem Area. While the remaining 39 % (10 lps) is supplied from other areas in and around the Mekele town. The existing population is estimated to be around 120, 000 and the population growth of Mekele and the water demand per capita per day for 10 years is given in table 10. (Devecon, 1992)

Year	2000	2005	2010
population	115,400	140,400	168,400
per capita demand l/s/d	35.0	41.9	48.9
domestic demand m^3/d	4040	5,880	8,230
public demand m^3/d	1620	2,060	2,470
losses m^3/d	850	1,590	2,140
max. day factor	1.2	1.2	1.2
max.day demand m^3/d l/s	7,810 90.4	11,440 132.4	15,410 178.3

Table 10. Summary of water demand, after Devecon (1992)

One can deduce from the table that the population of Mekele is in a fastly increasing trend. Accordingly the water demand increases. Therefore, to overcome the possible shortage of water after the indicated years require due attention.

5.6. GROUNDWATER RESERVE ESTIMATION

In order to estimate the volume of water available as a reserve, the following assumptions were made.

- The porosity of limestones ranges between 10 and 30 % (Freeze and Cherry, 1979). The limestone in the study area is affected by fracturing and dissolution cavities. Thin section analysis indicates that 15 % of the limestone is affected by fracturing. Taking the above observations the minimum effective porosity of limestone is considered be 0.15.

- According to Freeze and Cherry (1979) the porosity of Shale is in a range between 0 and 10 %. The shale in the study area is highly affected by the dolerite intrusion and other tectonic activities after its deposition. It is also intercalated with sandstone, limestone, and marl which could increase its effective porosity. Therefore 0.1 effective porosity is assumed in the calculation.

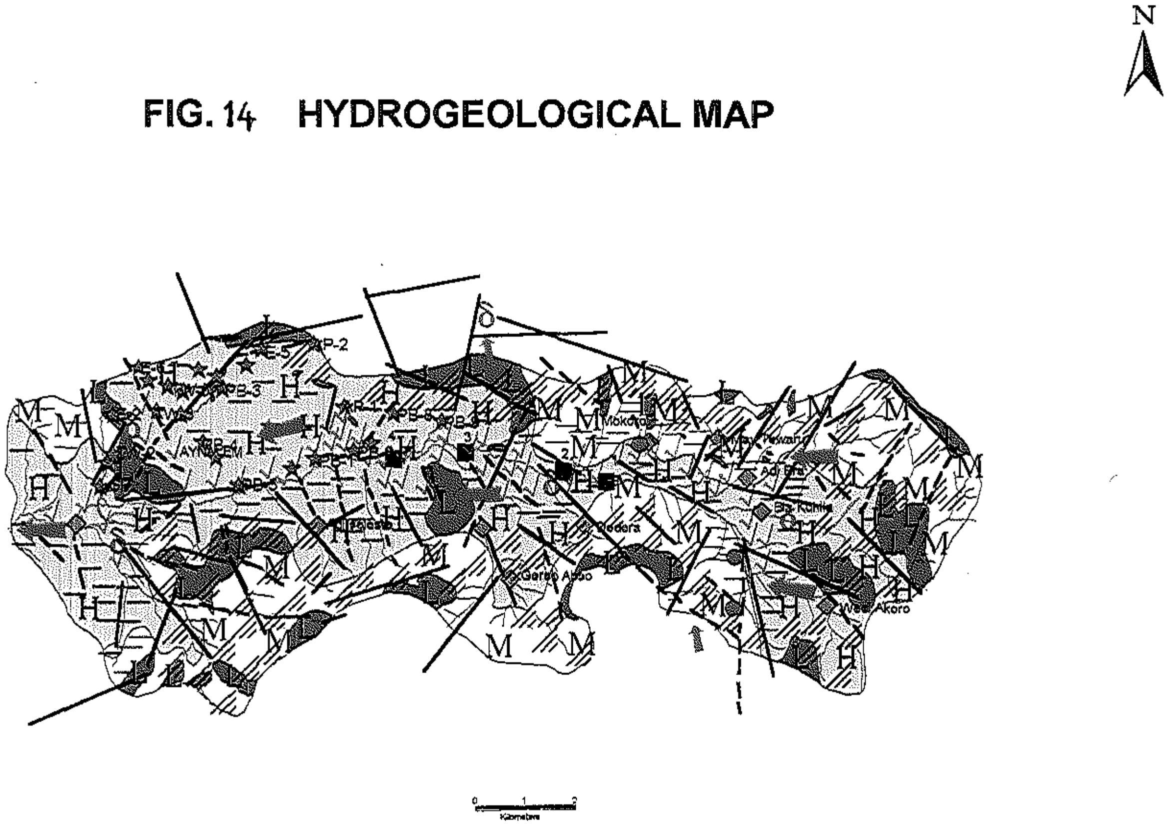
- The effective porosity of dolerite is less than that of shale. The fracturing of the dolerite is discontinuous as observed in the well logs. Therefore 0.08 effective porosity is used for the calculation.

- From bore hole logs, the most productive units is about 25 m thick.

The reserve is then calculated by considering the aerial coverage of each of the above lithologies. The limestone constitutes 50 % of the total area and covers 50.2 km^2, shale marly limestone unit covers 35 % (35 km^2) and the dolerite (15 %). Then the reserve is obtained by multiplying the effective porosity of each unit by the area coverage and the average aquifer thickness. The result shows a total reserve of $3.05 \times 10^8 m^3$.

This is a mere approximation because, the lateral extent of each lithologic unit may change with depth and the effective porosity values incorporate more subjective considerations. Therefore, the result gives only a rough picture.

FIG. 14 HYDROGEOLOGICAL MAP



LEGEND

- Shallow wells
- Borehole
- Flow
- Spring
- Pond
- Transition Zone
- Recharge Zone
- Discharge Zone
- H High Permeability
- M Moderate Permeability
- L Low Permeability
- Drainage
- Structure
- Inferred structure
- General groundwater movement direction
- Local groundwter movement
- River Gauging Station

LITHOLOGY

- Bedded limestone with swarms of dolerite dikes and sills
- Dolerite
- Limestone, shale & marly limestone intercalation

CHAPTER SIX

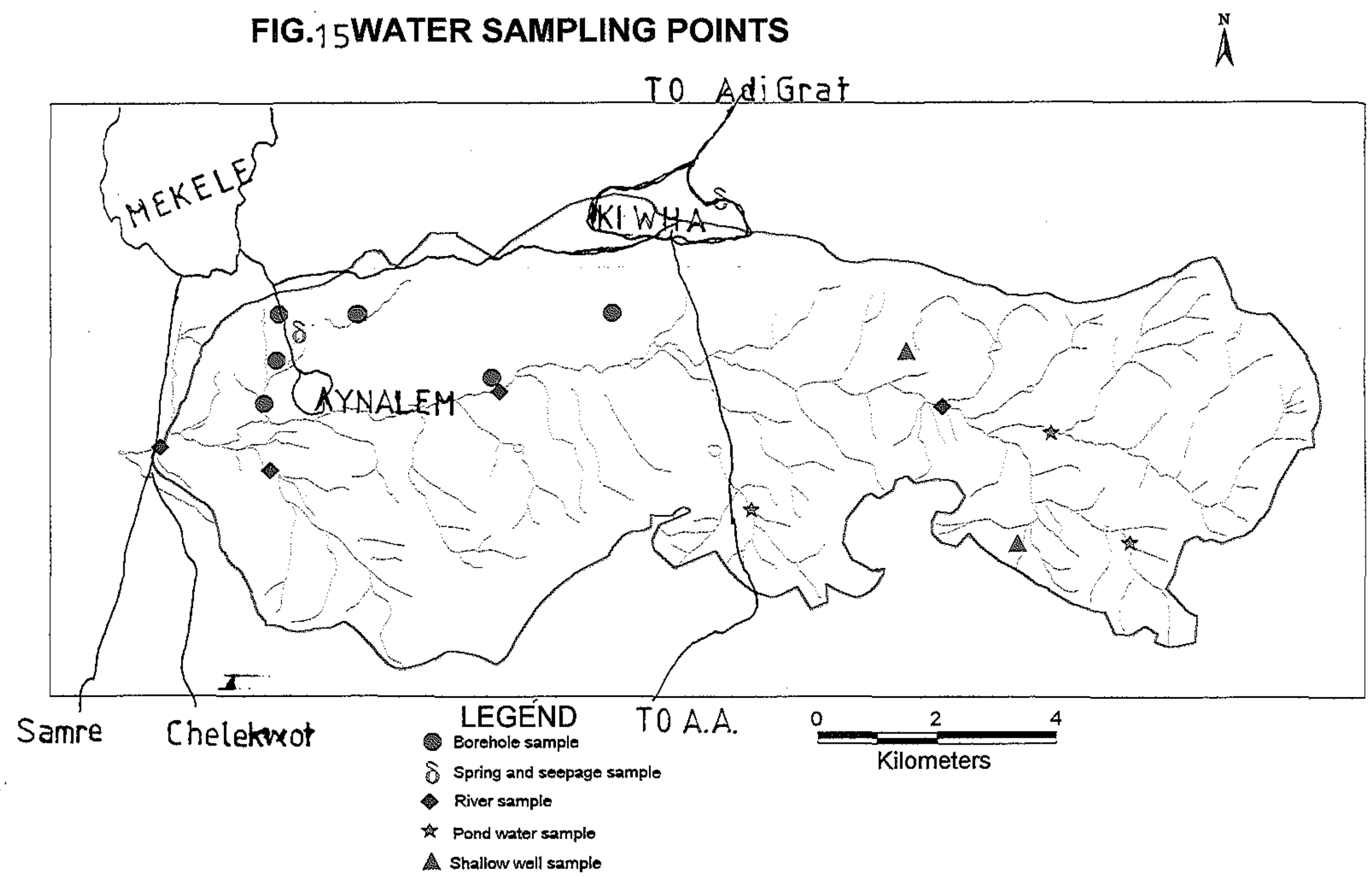
HYDROCHEMISTRY

6.1. INTRODUCTION

The objective of hydrochemical study is to check the suitability of the water for drinking & agriculture, to understand the groundwater flow system and the hydraulic relation between the surface & groundwater. To achieve these objectives a total of 14 water samples have been collected: 6 from bore holes, 3 from ponds, 4 from rivers and 1 from seepage. Sample locations are indicated in figure 15. The samples were analyzed in the Tigray National State Bureau of Water Resources Development, Mines & Energy, Water Quality Control Section. Additional samples were collected during the second fieldwork, which include 2 bore hole, 1pond & 1 shallow well and analyzed in the chemical laboratory of Geological Survey of Ethiopia and 4 shallow well & river samples were analyzed for major cations in the Department of Geology of the A.A.U. Previous chemical data have also been gathered and utilized. Devecon (1992) analyzed 13 bore hole samples, of which 3 are collected from localities in and around the Mekele town, and are used in the interpretation of the water chemistry of the area.

The data and results produced by this and previous works have been scrutinized and checked for charge balance. Those chemical data with erroneous values have been discarded and have not been used in this study.

FIG.15 WATER SAMPLING POINTS



For example, the results of Water Quality Control Section of the Tigray Region does not correspond with the other results in that, there is unexpectedly high (Na+K) content. This may be because the (Na+K) concentration have been obtained form principle of electrical neutrality. The analytical results of the previously collected and the presently obtained data are presented in table 11.

6.2. Chemical composition of water samples

The constituents contained in the chemical analysis results include cations such as calcium, magnesium, sodium & potassium, and anions such as bicarbonate, carbonates, sulfate, chloride & nitrate and both expressed in ionic form. The chemical composition of the waters form the area is very variable but Ca and Mg dominates the cations and bicarbonate and sulfate dominate the anions.

6.2.1 CATIONS

Calcium (Ca^{++}) and Magnesium (Mg^{++}) are the most dominant cations and are followed by low amounts of Sodium and Potassium (Na +K). The concentration of calcium varies between 5.3 to 14.2 milliequivalent per liter and that of magnesium varies between 0.56 and 2.2 milliequivalent per liter for bore hole samples. The sodium & potassium value vary between 1.2 to 3 and 0.03 to 0.1 milliequivalent. per liter respectively. Ca and Mg also dominate the chemistry of ponds and rivers.

The variability in the concentration of the cations can be explained in terms of the geology. The high calcium content corresponds to the lithology of the area where the limestone is the main aquifer unit. The relatively low magnesium value indicate that, the dolerite which contains ferro-magnesian minerals has a little influence on the chemistry of groundwater.

6.2.2. ANIONS

The dominant anions are bicarbonates in most bore hole samples and in all river and pond samples. The range of variation of carbonates in bore hole samples is from 3.2 to 5.6 milliequivalent per liter. The second major anion is sulfate with values ranging from 1 to 10.1 milliequivalent /liter in the Aynalem wellfield and up to 33.4 milliequivalent per liter in the boreholes of the Mekele town. The nitrate concentration is low in the wellfield, which indicates the wellfield to be free of anthropogenic rural pollution. The nitrate level is pretty below the WHO drinking water standards (50 milligrams per liter).

6.3. OTHER PARAMETERS

6.3.1. Electrical Conductivity (EC)

The electrical conductivity of water is proportional to the amount of dissolved substances in the water, that is the higher the concentration the higher the conductivity. The electrical conductivity measured during the first field work vary from 567 to 1172, 199 to 290, and 502 to 1810 μS/cm for bore holes, ponds and river samples respectively. The low EC value of the pond samples indicate the absence or little influence of groundwater. The hydrology of the ponds is dominated by surface water. This might indicate indirectly that the static groundwater is lower than the bed of the reservoir. That is the reservoirs are sources of indirect recharge to groundwater. The EC of river samples are low up stream indicating low residence time in which the sustained flow comes from upstream reservoirs. However, the EC values of river samples is higher down stream, because of human interference and concentration resulted from evaporation.

6.3.2. Total Dissolved Solids (TDS)

Total dissolved solids include all the solid substances in solution. It is directly related to the electrical conductivity. The TDS measured for bore hole samples vary between 400 and 2665 mg/l and the highest values recorded are for those first 3 bore holes (table 12) which are located in the Mekele town. According to the World Health Organization drinking water standards (1984), the limit of general acceptability is 500 mg/l or less. The maximum permissible limit is 1500 mg/l. Therefore, the mentioned values for the wells, springs and rivers of the Aynalem well field are within the limit of the allowable values (with the exceptions of the bore holes at the Mekele).

6.3.3. Calcium Magnesium Ratio (Ca^{++} / Mg^{++})

Groundwater that is influenced chemically by dissolution of calcite or dolomite can also be influenced by other minerals that exert some control in the concentration of Ca and Mg. For example the dissolution of gypsum can cause large increase in Ca concentration. The Mg concentration depends on the amount of magnesium in carbonate lithology or other sources of Mg. The proportion of calcium and magnesium tells the importance of calcium or magnesium bearing lithologies in the chemistry of the groundwater. In the study area all water samples show values greater than 1. The value range from 4.6 to 6.4. This suggests that the most important source rocks is the limestone, while the dolerite, which contains predominantly Mg has little significance.

6.3.4. Sodium Adsorption Ratio (SAR)

Sodium concentration is an important factor in classifying water for irrigation. Because sodium reacts with soils and reduce its permeability which makes cultivation difficult. The salinity laboratory of the US Department of Agriculture recommended the SAR as an index for sodium hazard and defined it as:

$$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}}$$

Where the concentration of the constituents are expressed in milliequivalent per liter.

Water class	Alkali Hazard (SAR)
excellent	up to 10
good	10-18
fair	18-26
poor	>26

Table 11. Water classification for SAR, after Todd (1959).

Ninety percent of the water samples have SAR less than 1. Therefore, there is no much danger of sodium hazard.

6.3.5. HARDNESS

Hardness results from the presence of divalent metallic cations of which calcium and magnesium are the most important once. Because of their adverse action with soap, hard waters are unsatisfactory for household cleaning purposes. According to Todd (1980) Hardness (H) is expressed as:

$$H = 2.5\, Ca + 4.1\, Mg$$

Where Ca and Mg are measured in milligram per liter as the equivalent of calcium carbonate. In the present work this method has been used to determine the total hardness of the water samples (table 12). For classification of range of hardness concentrations Hem (1989) used the following classification.

Hardness range (mg/l CaCO3)	Description
0-60	Soft
61-120	Moderately soft
121-180	Hard
>180	Very hard

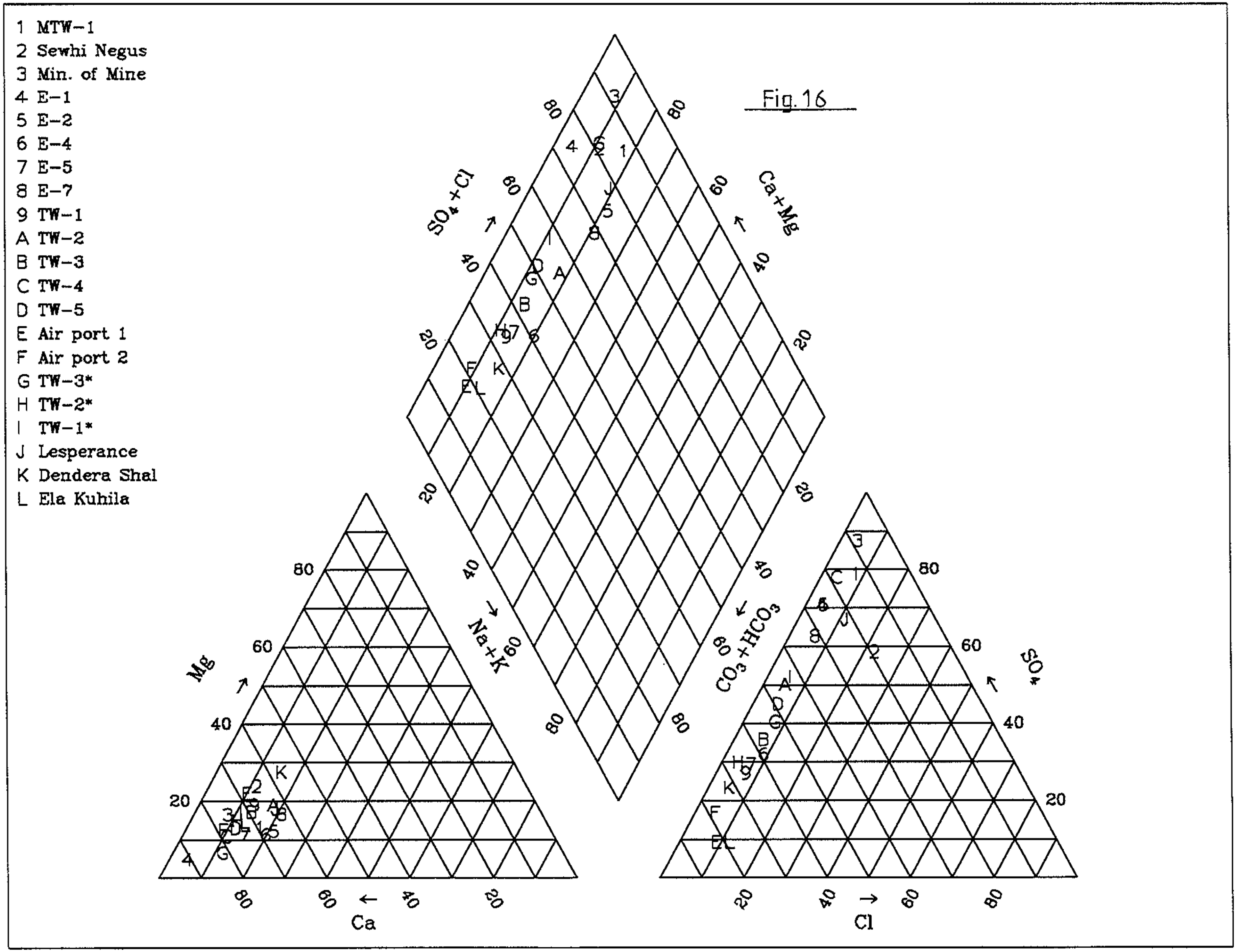
Table 12. Classification of Hardness values.

Based on the above classification, all bore hole samples fall in the very hard water class. Springs, rivers and shallow wells fall in the hard water class.

6.3.6. pH

It is defined as the negative logarithm of the hydrogen ion activity in water at 25°C. pH of 7 has equal H^+ and OH^- activities. pH 7 is termed as neutral. The values above and below this values indicate the alkalinity and acidity of the water respectively.

The pH of borehole samples ranges between 7.0 and 7.7 and for ponds and rivers samples it ranges between 7.8 and 8.5. Generally the results are within the permissible limit of the drinking water quality according to the World Health Organization (WHO) drinking water standards (1984) which is 6.5-8.5. Therefore, the pH values of water samples of the study indicate that there is no danger of extreme acidity or alkalinity of the water.



1 MTW-1
2 Sewhi Negus
3 Min. of Mine
4 E-1
5 E-2
6 E-4
7 E-5
8 E-7
9 TW-1
A TW-2
B TW-3
C TW-4
D TW-5
E Air port 1
F Air port 2
G TW-3*
H TW-2*
I TW-1*
J Lesperance
K Dendera Shal
L Ela Kuhila
Fig.16
SO_4+Cl
Ca+Mg
Na+K
CO_3+HCO_3
Mg
SO_4
Ca
Cl
20
40
60
80

well label	Ca	Mg	Na	K	Cl	HCO_3	NO_3	SO_4	F	pH	Sio_2	TDS	SAR	Hardness	Date of analysis
MTW-1	28	5.2	7.1	0.1	3.2	5.2	3.2	30.7	0.02	7.2	29	2644	1.7	1655.84	1992
Sewhi Ngus	15.2	5.6	2.5	0.2	5.2	4.4	5	13.5	0.02	7.5	28.5	1897	0.8	1035.52	1992
Min. of MInes	27.6	6	3	0	1.6	3.2	1.6	33.4	0.02	7.0	36	2665	0.7	1675.2	1992
E-1	11.8	0.6	0.6	0	0.6	3.6	0.6	10.1	0.02	7.6	51	974	0.8	619.52	1992
E-2	10.5	1.9	3.4	0	0.6	3.6	0.6	10.1	0.02	7.6	50	1038	1.4	618.48	1992
E-4	6.2	1.0	1.8	0	0.8	5.2	0.8	2.8	0.02	7.2	40	601	0.9	359.2	1992
E-5	6.5	1.0	1.3	0	0.6	5.2	0.6	2.4	0.02	7.5	38.5	560	0.7	374.2	1992
E-7	5.3	1.4	1.8	0	0.8	4	0.8	8.0	0.02	7.7	42	811	1.0	333.88	1992
TW-1	6.1	1.7	1.2	0	0.6	5.6	0.6	2.3	0.02	7.5	48.5	542	0.6	388.64	1992
TW-2	7.4	2.2	2.1	0	0.6	5.2	0.6	5.8	0.01	7.6	45	704	0.9	478.24	1992
Tw-3	6.1	1.5	1.2	0	0.6	4.8	0.6	3.0	0.02	7.0	41.5	593	0.6	378.8	1992
TW-4	11.7	1.6	1.5	0.1	0.6	2.8	0.6	11.9	0.02	7.1	57	1000	0.6	663.72	1992
TW-5	7.6	1.3	1.2	0	0.6	4.8	0.6	4.4	0.02	7.5	49	643	0.6	443.96	1992
Airport 1	5.9	1.9	0.9	0	0.6	5.4	0.7	0.6	0.02	7.5	38.3	609	0.5	388.48	1995
Airport 2	5.1	0.8	0.6	0	0.3	4.7	0.4	1.0	0.02	7.3	25.2	399	0.4	294.36	1995
TW3	7.7	0.6	1.1	.03	0.7	4.8	0.3	3.7	-	7.13	-	702	0.5	414.52	1998
TW2	6	1.2	0.9	.02	0.4	6.7	0.01	3.0	0.02	7.67	-	-	0.5	359.04	1997
TW1	7.7	1.8	1.2	0	0.6	4.6	0.2	5.6	0.02	7.25	26	-	0.5	473.56	2000
Lesperance	11.7	3.3	3.5	0	2.1	4.1	0.2	12.5	0.02	7.57	25	-		747.36	2000
Dendera well	5.4	2.6	1.5	0	0.5	7.1	0	2.3	0.02	7.15				397.92	2000
Pond	2.1	0.4	0.3	0.1	0.4	2.6	0	0.3	0.02	8.3				124.68	2000
River	1.7	0.8	1.1	0										124.36	2000
Spring	2.2	1.0	1.0	0										159.2	2000
Spring	3.3	0.8	0.8	0										204.36	2000
Igri- Hariba	2.9	0.7	0.7	0										179.44	2000

Table 12. Water Chemistry, cations and anions in meq/l silica and TDS in mg/l, hardness a $CaCO_3$.

The observations can be explained in terms of the geology and groundwater evolution along its flow path form east to west. Wells in Eastern part of the well field plot at low Ca and TDS. This is also true for Na, Mg, SO4 and Cl. Wells in the western part of the catchment are characterized by high content of these chemical species. A clear trend of variation is observed indicating a hydraulic link between the two extremes.

CHAPTER SEVEN

CONCLUSIONS AND RECOMMENDATIONS

The presence of extensive fracturing, sedimentary bedding and cavernous features in the limestone unit played the most important role in controlling the groundwater movement and occurrence in the catchment. The presence of inter-catchment faults and groundwater inflow & outflow zones indicate that the groundwater divide and surface water divide does not coincide. Although there are local deviations, the general groundwater flow direction is towards the west following the general topography.

The limestone is the main aquifer unit of the area. High values of transmissivity and permeability have been calculated 29.2-74.4 m/day. The shale, marl and limestone intercalation unit has lower transmisivity and permeability values 1-1.4 m/day. The dolerite has the lowest values ranging between 0.02-1 m/day. The disappearance and reappearance of the river along its course revealed the presence of underground channel indicating cavernous features affect the limestone.

Pumping test data show a direct hydraulic connection between the wells and the Aynalem River.

The average annual precipitation is 639 mm out of which 57 mm (9%) is detained by the soil and ultimately joins the groundwater. In addition there is recharge through the stream channel amounting 43 mm. The recharge form the ponds could also be significant. Therefore the water demand indicated is by far smaller than the annual recharge.

The groundwater reserve of the catchment has been calculated to be 3.05×10^8 m^3. Where as the present groundwater demand is 2.85×10^6 m^3. While the present consumption is less than half of the demand (1.12×10^6 m^3). Forty percent of the total consumption comes from wells other than the Aynalem well field. The calculation of the water balance of the area indicate that there is a ground water recharge of 57mm (5.7×10^6 m^3) annually.

The ponds in the area are built on limestone unit and across fault lines. They are characterized by continuous loss of their water reserve. Field observations and water level data suggest that the ponds contribute significant amount of their reserve to the groundwater.

From the hydrochemical data, it can be drawn that there are at least two types of waters. Ca-HCO_3 dominated water type at the eastern part of the well field and Ca-SO_4 dominated waters at the western extreme of the catchment with a clear evolutionary tread between the two.

The quality of most of the wells in the well field satisfies the WHO (1984) drinking water standard. That is, the TDS is less than the maximum permissible limit, 1500 mg/l. They are entirely free of anthropogenic pollution. Ca-HCO_3 type water dominates the well filed. However there is gradual increase in SO_4 content toward the west (Mekele Town).

RECOMENDATION

The following recommendations are forwarded.

- Since the structures play an important role in the groundwater circulation a detailed structural mapping is necessary.
- Proper geophysical surveys are needed to understand the extent and type of aquifer.
- Isotope hydrogeology is recommended to refine the conclusions made on the source of recharge, the relation between surface and groundwater, and the amount of groundwater inflow and outflow to and out of the catchment.
- When need arises for additional wells it would be better to located the well in the upstream part of the existing wells and in the left bank of the Aynalem river. This on one hand facilitates the characterization of the aquifer system and on the other hand good quality water can be obtained as low TDS and sulfate content characterize this zone.
- The wells in the area are concentrated at only one side of the catchment with area coverage of 17 Km^2. Therefore, the responsible department should avoid the abstraction of nearby wells at the same time to minimize the effects of fast drawdown of the static water level.

Appendix 1. Record of solar radiation and sensible heat, after Macdonald (1975)			
Months	Solar radiation including Albedo allowance mm/day	Back radiation from the earth mm/day	Dynamic diffusion process (mm/day)
O	6.563	1.968	0.752
	6.816	2.287	1.318
	6.571	2.373	1.381
N	6.419	2.47	1.635
	5.941	2.378	1.42
	5.719	2.421	1.634
D	5.533	2.225	1.28
	5.526	2.246	1.468
	5.517	2.257	1.432
J	5.573	2.488	1.82
	5.695	2.317	1.581
	5.123	1.734	1.492
F	4.973	1.517	1.246
	6.011	1.914	1.343
	6.84	2.542	2.141
M	7.179	2.409	1.858
	7.363	2.198	1.314
	6.152	1.669	1.911
A	7.62	2.257	1.427
	7.596	2.377	1.758
	6.769	1.965	1.945
M	7.929	2.774	2.979
	7.341	2.265	1.605
	6.539	1.855	1.547
J	5.475	1.201	0.819
	5.95	1.486	1.085
	5.063	1.088	0.569
J	5.063	0.995	0.575
	5.07	0.987	0.444
	4.981	0.976	0.334
A	3.781	0.542	0.137
	5.002	1.006	0.239
	4.726	0.879	0.214
S	4.988	0.984	0.178
	5.229	1.196	0.357
	6.1	1.606	0.639

Appendix 2a. Monthly average temperature at Mekele

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1960						27.1	21.9	21.5	22.7	23.5	22.8	22.7
1961	21.7	24.8	25.1	26.3	26.6	27.9	22.5	22.3	23.2	23.8	23.5	22.6
1962	24	23.4	24.9	25.9	27.6	27.1	20.8	21.2	24.3	23.6	21.4	21.7
1963	22.3	24.2	24.4	26.2	27.2	28.2	25.2	22.5	24.2	22.9	21.7	22.4
1964	21.1	23.6	25	25	25.6	27.5	23.3	23.2	25.6	25.5	24.2	23.3
1965	24.7	26.8	27.8	26.7	28.9	28.8	23	23.1		23.6	23.5	22.6
1966	24.4	24.6	25.7	26.5	28.7	29	25.6	23	25.9	25.1	23.6	24.3
1967	24.9	25.7	26.9	27	28.6	29.2	25.4	24	25.2	25.2	23.4	24
1968	24.4	26.4	26.5	26.7	27.6	27.9	22.7	22.3	25.4	23.9	23.2	23.6
1969	24.1	24.4	26.1	26.1	27.4	27.3	23.2	24	26.6	25.2	23.5	
1970	24.1	24.8	25.1	27	27.8	29.9	24.5	23.7	25.3	26	24.7	24.3
1971	25.5	26.9	26.9	27.3	29.4	29.2	24.8	22.6	25	24.4	23.3	22.8
1972	23.1	25.5	25.5	27.2	26.8	27.4	24.4	24.1	25.6	24.9	23.6	23.4
1973	25.2	26.4	26.9	26.1	27	27.4	24.5	24.9	26.6	25.2	24.9	24.7
1974	26.5	27	28.7	28.3	28.4	29.4	24.6	23.9	25.4	22.3	21.7	20.3
1975	22	22.5	21.8	24.7	24.8	25.9	21.7	21.8	24.9	22.6	20.5	21.2
1976	21.4	22.4	24	24.4	26.2	24.3	21.9	20.8	23	22.3	20.2	20.1
1977	21.5	23.1		23.7	24.8	25.2	22.6	21.4	24.3	22.9	21.1	21.1
1978	21.9	21.9	23.1	25.8	25.2	22.5	21.8	21.6	24.1		21.3	
1979	21.4	23.4	24.1	24.8	26.9	26.2	20.5	21.7	24.7	22.4	20.6	20.5
1980	20.3	23	24.3	24.7	24.6	25.9	23.3	22.7	24.8			
1981	23.3	23.8	25.6	25.7	26.8	25.7	21.9	22.4	24.2	23.6	22.6	22.3
1982	23.1	24.2	24.1	25.3	26.8	27.7	22.8	22.2	23.6	23.5	22.5	22
1983	23.2	25.2	24.4	25	25.8	27.5	23.8	22.2	24.1	22.8	22.7	22.8
1984	22.9	25.1	26.8	26.7	26.6	27.5	25.8	22.3	24.9	24.1	23.5	23
1985	23.1	24.5	26.3	27.2	26.7	26.8	23.8	23.7	24.3	24.2	23.1	21.7
1986	23.8		24.5	24.1	25.5	27.2	23.4	22.5	24.1	22.8	22.8	22.1
1987	22.7	24.6	24.4	21.3	25.7			23.3			23.7	22.4
1988	22.8	23.1	24.5	25.9	26.2	27	22.3	21.2	23.3	24.1	22.6	21.2
1992	21.7	23.2	24.5	25.4	26	27.6	23.2	19.2	22.8	22.5	20.2	20.8
1993	20.7	21.8	23.6	22.2	24	25.3	22.3	22.9	24.4	23.1	21.8	21.5
1994	21.9	22.9	24.2	24.9	26.1	25.7	21.3	21	22.5	23.1	21.9	21.6
1995	22.1	24	24.6	24.6	25.8	28.2	22.9	22.1	23.9	23.4	22.8	22.8
1996	23	24.9	24.9	25.6	25	24.4	23.2	22.5	24.9	23.7	22.1	21.6
1997	23.3	23.5	25.7	25.5	27.4	25.8	22.8	23.1	25.7	23.3	22.6	23.1
1998	23.7	25.2	26.1	27.3	27	27.8	22.4	21.3	23.9	23.3	22.2	21.8

Appendix 2b. Monthly average temperature at Mekele

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1960						12.3	12.4	11.5	9.2	9.4	8.5	8.6
1961	8.6	9.8	10.9	12.4	12.7	12.9	11.9	11.9	10.5	9.6	8.2	8.9
1962	8.9	9.5	10.8	12.8	13.1	11.5	11.7	11.6	10.1	9.8	9.9	9.3
1963	8.1	8.6	11.7	12	12.9	12.8	11.7	12	11.2	8.7	9.4	8.8
1964	8.6	9.5	11.3	12	12.4	12.5	11.8	12.1	11.2	11.6	12.3	9.4
1965	11	10.9	12.1	13.4	14.2	14	12.3	12.4		10.7	8.4	8.9
1966	8.5	10.4	10.7	13.8	14.8	13.8	13	12.5	11	10.7	10.9	9.3
1967	9.4	10.8	12.2	13.9	14.7	14.1	13.3	12.5	12	11.5	10.2	7.4
1968	7.2	9.3	12	13.3	13.6	12.7	12.9	11.8	11.5	11.1	10.7	8.3
1969	8.3	9.2	11.5	12.6	14.8	13.5	12.5	12.1	12.1	12.2	10.1	
1970	10.3	10.4	11.9	13.9	14.2	14.3	13.1	12.6	11.8	11.1	9.7	7.3
1971	9.2	10.3	11.9	13.9	14.8	14.3	13	13	10.9	12.5	8.4	7.4
1972	8.5	9.3	11.4	13.7	13.4	13.3	12.8	12.9	12.1	12	9.7	8

1973	9.4	9.9	12.1	14	13.8	14.2	12.6	12.3	12	12.4	11	11
1974	9.4	9.9	11.8	13	14	14	12.7	13.1	12.7	11.1	10.1	7.8
1975	8.9	9.7	10.7	13.1	13.4	13.5	11.5	11.8	11.9	11.2	8.4	8.4
1976	9.3	10.9	12.2	12.8	14	12.6	12.3	12	11.7	10.7	9.5	9
1977	9.3	10.8		12.4	13.2	13.1	12.2	11.8	11.5	11.3	9.8	8.2
1978	8.4	8.9	9.7	9.5	9.7	10.6	9.6	9.2	8.5		8.8	
1979	9.7	11.4	12.3	14.2	15.3	13.9	12.6	12.1	11.8	11.7	10.4	5.3
1980	5.1	5.8	7.8	8.9	10	10.2	8.9	7.7	11.8			
1981	8.9	10.7	11.7	12.5	13.5	13	12.4	12.3	11.2	9.9	9.4	8.3
1982	9.3	9.4	11.7	12.3	13.2	13.1	12.6	12.5	10.6	9.2	8.1	6.4
1983	8.7	8.9	10.2	10.8	11.5	12.3	11.3	11	9.9	9.2	9.2	7.9
1984	6.9	7.8	10	11.4	12.2	11.9	11.6	11.7	10.2	9.3	8.3	7.1
1985	6.5	7.1	10.3	12.3	12.1	12.5	14.8	11.4	10.8	9.5	9.9	8.4
1986	6.7		9.4	10.2	11.7	11.9	11.1	11.6	10	10.6	9.6	8.3
1987	1.6	3.5	4.2	9.2	10.8			11			8.6	8.4
1988	9.3	9.8	11.2	12.3	12.5	12.1	9.3	11.1	11.6	9.1	4.3	2.1
1992	9.9	9.7	11.9	13.2	13.8	13.6	12.4	12.4	11.2	10.9	10.4	10.6
1993	9.6	9.6	11.7	12.5	13.2	13	12.6	12.6	11.7	12.1	10.5	9.4
1994	9.5	10.6	11.7	13.8	14.4	12.9	13	12.9	10.7	10.6	10.6	9.2
1995	9.3	9.8	11.9	14	14.5	13.7	12.7	13.3	11.3	11	10.1	10.4
1996	9.6	10.6	12.5	13.3	13.6	12.6	13.1	13.2	11.7	11.2	10.2	9.4
1997	9.3	10.1	12.4	13	13.5	14.4	13.2	12.7	12.4	12.3	12.3	10.3
1998	10.8	10.2	12.8	14.9	14.5	14.4	14	13.9	12.6	11.5	8.9	8.3

Appendix 3. Summary of Hydrometric Discharge data of Aynalem River

Year		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1992	I	0	0	0.02	0	0.065	0	0.17	0.79	0.038	0	0.021	0
	II	0	0	0.013	0	0.36	0	0.52	2.03	0.074	0	0.074	0
	III	0	0	0	0	0	0	0	0	0	0	0	0
1993	I	0	0	0	0.103	0.075	0.007	0.166	1.08	0.443	0.034	0.014	0.007
	II	0	0	0	0.409	0.2	0.038	0.2	9.1	4.149			
	III	0	0	0	0	0	0	0	0.04	0.005			
1994	I	0	0	0	0.002	0	0.04	0.188	3.84	0.94	0.031	0	0
	II	0	0	0	0.023	0	0.36	0.756	15.2		0.23	0	0
	III	0	0	0	0	0	0	0	0.01		0	0	0
1995	I	0	0	0.003	0	0.011	0.101	0.145	0.53	0.03	0	0	0
	II	0	0	0.038	0	0.074	0.234	0.2	0.8				
	III	0	0	0	0	0	0	0	0.02				
1996	I	0.004	0	0	0	0.019	0.081	0.341	0.22	0.039	0	0	0
	II	0.002	0.001	0	0	0.217	0.217	2.47	0.27	0.038	0.001	0	0
	III	0.001	0	0	0	0	0	0.002	0.01	0.001	0	0	0
1997	I	0	0	0	0	0.047	0.04	1.7	0.51	0.004	0	0	0
	II	0	0	0	0	0.409	0.027	10.2	1.35	0.015	0	0	0
	III	0	0	0	0	0	0.007	0	0	0	0	0	0
1998	I	0	0	0	0	0	0.274	2.02	2.35	0.49	0.179	0.206	0.147
	II	0	0	0	0	0	1.1	4.71	0.83	1.35	0.084	0.104	0.074
	III	0	0	0	0	0	0	0.007	0.01	0.084	0.058	0.05	0.27

I Monthly runoff in million cubic meter
II Maximum discharge in cubic meter
III Minimum discharge in cubic meter

Appendix 4a.Monthly mean Relative Humidity at 0600 L.T. -Mekele												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1960	83	73	83	75	82	78	92	95	87	73	73	82
1961	78	85	75	73	59	63	91	92	87	76	75	78
1962	76	61	66	62	71	55	83	84	80	66	73	71
1963	75	73	67	79	64	65	84	87	73	57	61	85
1964	84	76	63	62	57	56	90	95	83	79	68	84
1965	70	56	61	70	49	53	81	91	79	76	68	78
1966	66	80	71	67	57	60	81	92	83	72	67	69
1967	67	70	68	71	66	59	88	87	83	73	80	80
1968	73	85	66	77	65	76	91	92	64	52	75	79
1969	85	85	76	78	75	65	91	92	87	69	72	67
1970	80	77	77	65	54	65	87	94	87	76	70	79
1971	76	64	68	66	72	72	88	90	81	71	80	77
1972	74	77	80	79	74	75	90	89	85	75	80	82
1973	82	73	75	76	74	73	82	90	78	73	69	60
1974	71	69	81	57	62	54	90	92	81	67	50	66
1975	59	75	68	70	53		88	95	84	69	72	62
1976	67	77		73	69	72	93	96	81	76	81	74
1977	85	68	72	67	67	69	95	97	84		82	80
1978	74	73	81	68	60	63	95	94	78	76	81	78
1979	83	73	71	67	71	73	89	92			64	63
1985			62			85	94	97	87	86		
1991							65	74	46	43	41	49
1992	55	49	47	38	34	32	73	86	66	57	61	50
1993	48	42	38	68	65	66	72	69	53	50	54	44
1994	45	47	46	36	28	39	68	74	55	34	48	42
1995	37	44	40	50	40	36	73	77	47	37	35	43
1996	47	37	42	34	43	49	59	70	44	33	39	34
1997	36	31	34	32	31	45	68	62	33	42	47	35

Appendix 4b.Monthly mean Relative Humidity at 1200 L.T. -Mekele												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1960	45	38	46	36	37	31	64	66	53	37	36	41
1961	32	41	39	47	27	31	76	69	46	36	44	44
1962	36	25	38	34	35	28	54	64	47	36	45	39
1963	41	39	33	45	39	35	68	64	43	32	46	43
1964	41	34	29	35	29	32	65	64	50	47	35	42
1965	30	29	30	41	22	25	55	66	34	36	41	33
1966	31	38	32	32	27	32	63	43	51	40	39	37
1967	31	28	32	35	33	31	64	65	49	42	44	38
1968	36	42	33	38	29	37	63	60	43	36	36	35

1969	46	42	46	43	42	29	64	63	45	34	30	26
1970	37	30	34	36	25	26	52	68	50	52	39	50
1971	42	29	34	29	37	40	58	62	42	36	39	37
1972	31	37	27	37	29	39	57	60	39	36	39	38
1973	36	23	27	25	32	25	57	61	43	38	39	31
1974	34	36	51	29	35	31	66	69	38	33	25	30
1975												
1976	30	39		37	36	44	69	69	48	39	48	36
1977	46	39	38	26	33	41	74	78	54		44	45
1978	44	36	39	32	23	32	70	69	38	38	43	44
1979	49	37	37	29	34	38	57	60	35	35	32	35
1980	41	43	34	35	26	32		68	49	40	35	34
1981	45	30	45	36	27	26	64	69	46	40	36	36
1982	42	40	38	40	33	23	48	68	41	43	48	44
1983	33	34	37	36	39	32	50	71	44	34	31	33
1984	32	22	31	24	33	33	56	55	42	28	35	45
1985	29		37	45	38	30	63	70	49	43	37	50
1991							65	74	46	43	41	49
1992	55	49	47	38	34	32	73	86	66	57	61	50
1993	48	42	38	68	65	66	72	69	53	50	54	44
1994	45	47	46	36	28	39	68	74	55	34	48	42
1995	37	44	40	50	40	36	73	77	47	37	35	43
1996	47	37	42	34	43	49	59	44	44	33	39	34
1997	36	31	34	32	31	45	68	33	33	42	47	35

Appendix 4c. Monthly mean Relative Humidity at 1800 L.T. -Mekele

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1960	69					58	84	89	79	88	64	76
1961	74	79	70	73	45		87	90	76	59	67	73
1962	70	53	62	53	53	42	75	84	68	51	60	65
1963												
1964	73	67	53	52	45	42	86	89	70	60	54	75
1965	61	49	47	60	36	36	71	83	54	54	61	64
1966	53	70	61	54	41	31	54	70	67	64	64	65
1967	57	58	64	47	40	34	73	75	46	45	56	53
1968	49	58	44	51	32	37	67	62	46	42	45	51
1969	62	59	56	49	43	34	71	66	52	36	38	38
1970	55	46	49	43	28	34	61	73	47	45	36	36
1971	55	40	41	41	42	44	64	64	45	43	52	48
1972	47	51	41	48	33	46	67	57	40	41	47	56
1973	47	29	38	29	34	31	65	65	45	46	42	44
1974	52	47	64	33	41	31	65	68	47	36	30	44
1975												
1976	47	61		48	43	49	68	74	51	42	55	48
1977	69	47	46	44	41	46	75	78	61		56	62

1978	53	54	61	35	28	38	77	73	45	43	52	57
1979	68	51	54	39	41	42	56	67	44	43	39	55
1980	62	63	49	49	34	41		75	53	43	40	43
1981	33	45	59	50	34	28	70	74	52	40	44	44
1982	57	64	51	52	39	27	56	73	47	47	62	63
1983	54	61	61	58	52	34	53	78	49	43	46	50
1984	49	34	41	31	44	39	65	63	54	32	52	59
1985	43				42	34	69	79	54	39	31	34
1991							70	81	53	52	51	68
1992	74	73	63	49	42	35	76	87	71	64	69	71
1993	71	63	52	75	71	67	78	72	55	56	61	55
1994	55	61	66	43	36	53	73	82	64	44	56	55
1995	50	55	54	59	45	40	78	79	50	38	43	64
1996	65	53	57	65	46	53	66	76	48	37	52	47
1997	58	48	55	51	35	47	74	64	33	53	62	54

Appendix 5. Mean monthly wind speed at Mekele in m/sec.												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1996	3.6	4	3.7	4.1	3	1.9	2	1.6	2	3.3	3.6	3.7
1997	3.25	4.87	3.86	3.79	3.61	2.3	2.26	1.5	2.3	3.5	3.7	3.8
1998	3.5	3.2	4.4	4.7	3.4	2.4	2.3	1.7	1.6	2.7	3.3	3.5
Monthly mean	***3.45***	***4.02***	***3.99***	***4.2***	***3.34***	***2.2***	***2.19***	***1.6***	***1.97***	***3.17***	***3.53***	***3.67***

Appendix 6.Monthly sum precipitation at Mekele												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1960	1.1	8.9	24	15.8	30.6	23.3	230.8	309.5	56.7	0	0	12.6
1961	3.6	19.7	39	90.6	17	53.1	400.3	376.5	79.8	5.1	20.9	0
1962	0	0	57	85.2	14.7	4.7	221.5	304.3	55.4	0	3.6	1.2
1963	2.1	1.3	12.3	94.7	20.4	23.5	248.7	163.1	15.3	0	15.9	8.3
1964	7.1	0	9.5	59.4	11.8	36.7	323.8	229.1	28.3	15	0	1.8
1965	0	13.7	28	23.8	2.1	14.6	144.4	284.2	14.4	0	0	0
1966	0.7	7.8	7.2	51.2	0	6.7	154.4	218	25.9	1	0	0
1967	0	0	18.6	44.8	10.2	38.3	270.5	280.3	11.6	5.6	2.2	0
1968	15.2	0	9.5	5	20.7	61.2	196	142.3	1.6	0	0	0
1969	20.3	1.7	118	43	47.3	0	183.6	184.4	38.9	0	0	0
1970	2.6	5.9	22.5	20.6	4	10.7	249.7	264.2	64.3	0	0	0
1971	0	0	26.8	4.2	60.1	33.7	91.8	205	20.9	0	0	0
1972	0	5.7	21.8	77.7	9	86.1	196.8	83.7	41.9	3	39	0
1973	0	0	0	42.8	16.7	27.6	214.3	145.8	46.5	2.2	0	0
1974	0	0	16.5	2.3	45.2	20	170.1	238	17.9	0	0	0

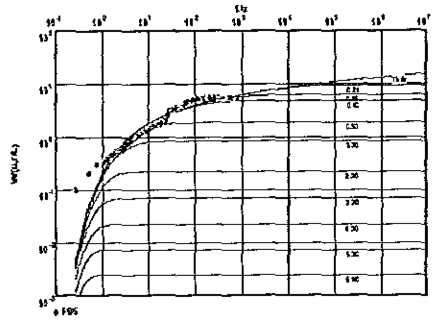
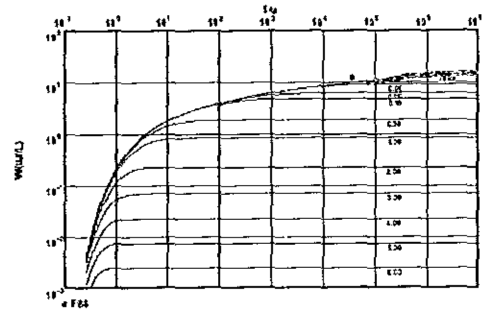
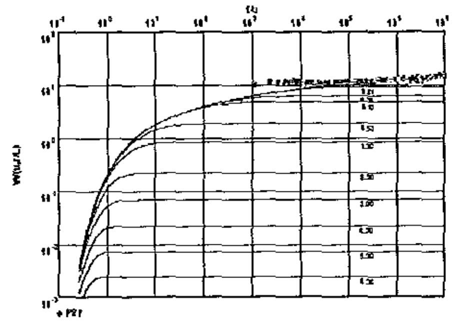
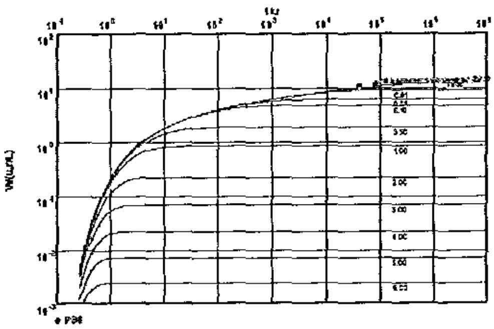
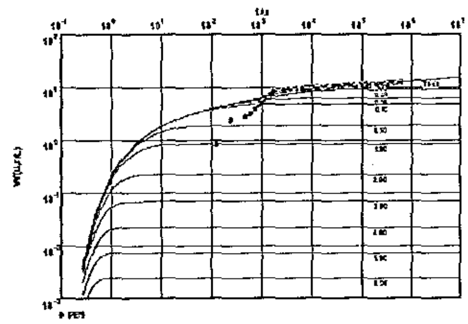
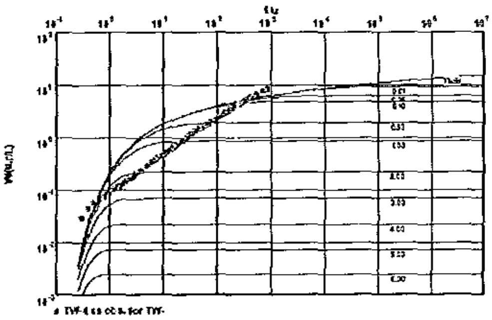
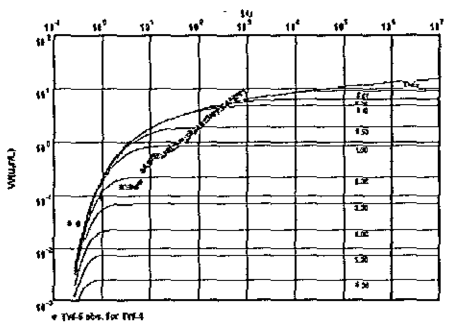
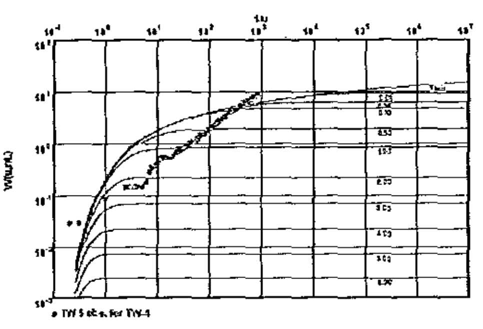
1975	1.4	20.8	18	21.5	10.6	100	185.1	293.1	120.7	0	0	0
1976	0	5.1		41.7	28.1	17.5	180.1	205.5	49.6	2.1	3.2	0
1977	0	0	19.3	5.4	77	56.5	204.6	251.2	62.9		0	0
1978	0	0	22.3	0	0.6	32.6	180.8	203.6	5.6	0	0	0.5
1979	0	0	2.5	40.9	103.8	30.8	63.3	98	28.5	0	0	0
1980	0	83.1	0	112.3	43.5	42.1		407.9	17.7	0	0	0
1981	0	0	23.4	5.6	11.3	0	149	205.3	22.9	0	0	0
1982	0	24.4	45.2	70.8	9.3	8	192.6	207.1	31.2	0	0	0
1983	0	11	4.6	27.5	106.3	1.8	244.3	255.1	35	1.6	17.4	0
1984	0	0	14.2	2.2	0	9.7	117.7	97.3	50.4	0	25.9	0
1985	1.8		24.7	126.8	37.4	14.6	129.4	180.8	20.6	0	0	0
1987	0	2	79.6	37.2	126.7	56.5	177.2	220.2	36.3	1.9	0	0
1988	0	29.3	0	10.1	37.6	6.7	380.3	394.9	59	0	0	0
1991							197.5	216.3	28.2	53.1	0	0
1992	8.7	2.1	38.5	1	30.7	6.2	140.7	233.1	1.3	2.1	54.2	8.3
1993	11.7	7.7	63.9	125	74.7	69	217.2	106.5	15.2	20	0	0
1994	0	5.3	0.4	43.8	0.8	67.6	147.9	317.3	70.1	0	1.8	2
1995	0	5.9	31.2	29.2	27.1	6.8	268.2	237.7	51.4	3	0	2.7
1996	1.4	0	59.5	12.5	92.2	47.9	109.2	224	7.1	0	31.4	1.1
1997	0	0	19.8	32.6	29.8	32.4	236.1	100.5	16.3	82.9	15.7	0
1998	10	12	0	10.6	22	48	289	318.8	31.7	22	0	0

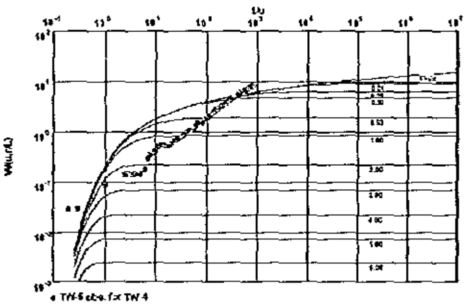
Appendix 7. Monthly Sum Evaporation at Mekele

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1992	116	126.4	172.1	224.7	244.3	256.6	114.4	52.2	116.7	179	161.8	128
1993	134.7	147.3	211.9	127.8	179.3	149.1	68.7	82.3	126.3	201	219.7	225
1994	233.4	187.1	202.4	265.8	308.4	177.7	85.2	110.8	153.4	229	195.1	206
1995	219.6	188.6	196.6	219.3			93.2	58.5	170.9	244	203.6	187
1996	151	246.1	176.9	132.5	224.1	173.5	118.8	61.6	203.2	232	213.8	262
1997	219.1	284.6	271.7	292.9	350.5	252.9	101.5	117.7	224.8	242	187.5	220
1998	165.5	235.6	302.2	374.1	391.2	419.7	127.6	75	173.6	232	317.2	357
mean	**177**	**202**	**219**	**234**	**283**	**238**	**101**	**80**	**167**	**223**	**214**	**227**

Appendix 8. Monthly sunshine hours at Mekele

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1992			9	9.4	9.8	8.1	5	4.3	6.9	7.9	6.9	9
1993	9.7	8.5	9.6	8.4		6.5	5.4	5.3	7.1	8.6	10.4	10.2
1994	10.3	9.9	9	9.5	10.1	6.4	5.4	5.1	7.9	10.5	9.8	10.2
1995	10.3	8.9*	9.3	8.8	9.3	9.2	5.4	5.1	8.7	9.8	10	9.4
1996	8.9	9.6	8.2	9.1	8.4	5.9	6.1	5.8	7.7	9.8	9	9.9
1997	9.4	9.8	8.5	9.1	9.6	8	6	6.5	8.4	8.1	10	10
1998	8.4	8.7	9.1	9.4	9.4	7.3	4.9	4.9	7.1	9.2	10.2	10.3
Monthly mean.	**57**	**46.5**	**62.7**	**63.7**	**56.6**	**51.4**	**38.2**	**37**	**53.8**	**63.9**	**66.3**	**69**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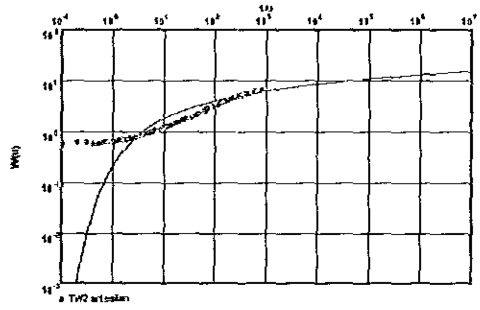
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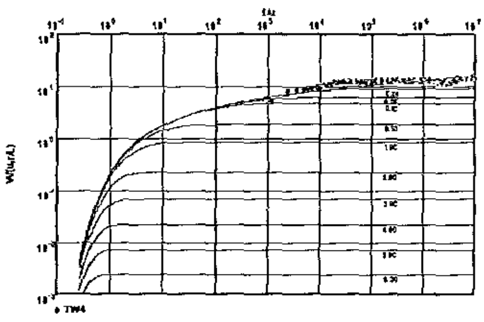
W(u)
TW2 artesian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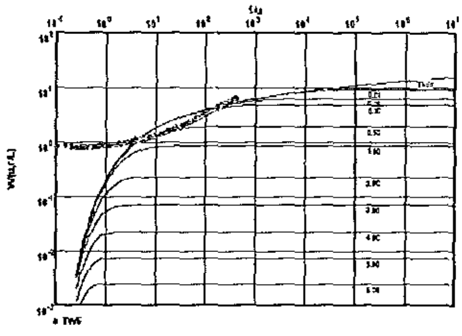
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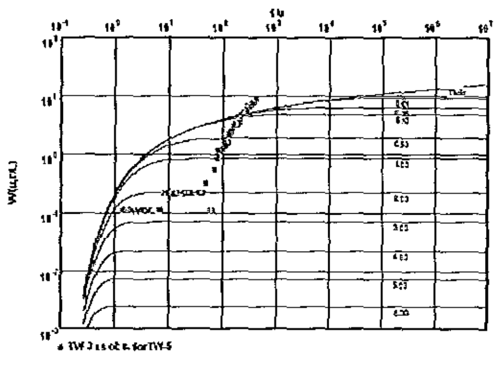

1/u
W(u,r/L)

well label	Coordinates		Depth (m)	Static water level (m)	Drawdown (m)	Aquifer thickness (m)	Pumping rate (l/s)	Transimissivity (m^2/day)	Hydraulic conductivity (m/day)	Aquifer Lithology
	Northing	Easting								
PB1	555814	1487574	120	11.22	13.7	30	21.7	**145**	**4.83**	**SSt/Dolerite**
PB1 Reco.	555814	1487574	120	11.22	13.7	30	21.7			
PB2	556590	1487731	117.5	31.3	36.87	21	15	**20.7**	**0.99**	**Dolerite**
PB2 reco.	556590	1487731	117.5	31.3	36.87	21	15.0	**16.3**	**0.776**	**Dolerite**
PB3	553966	1488966	120	20.55	3.12	53	90.0	**2630**	**49.7**	
PB3 Rec.	553966	1488966	120	20.55	3.12	53	90.0	**4030**	**76**	**Lmt / Dolerite.**
PB4	552880	1489018	120	15.15	8.55	30	21.73	**293**	**11.7**	**Dolerite**
PB4 Reco.	552880	1489018	120	15.15	8.55	30	21.73			
PB5	554288	1487046	104	13.33	74.07	41	2.0	**0.97**	**0.0236**	**Dolerite**
PB5 Reco.	554288	1487046	104	13.33	74.07	41	2.0	**0.942**	**0.0229**	
PB6	555361	1487382	75	19.73	1.54	30.5	21.73	**2260**	**74.4**	**Lmt/ Dolerite**
PB7	556956	1487873	65	8.01	9.49	20	80.0	**888**	**44.4**	**Lmt/Dolerite.**
PB7 Reco.	556956	1487873	65	8.01	9.49	20	80.0	**1030**	**51.5**	
PB8	557391	1488472	89.9	19.31	22.04	34	42.0	**500**	**14.7**	**Lmt /Gravel**
PB9	558355	1488334	71.5	16.26	29.43	16.5	5.4	**15.7**	**0.954**	**Lmt / SSt**
PB10	553478	1489350	98							
PB11	552477	1489131	75	9.8	10.58	13	21.73	**967**	**74.4**	**SSt**
PB12	553190	1488917	85	14.97	7.52	16	90.0			**Lmt /Dolerite**

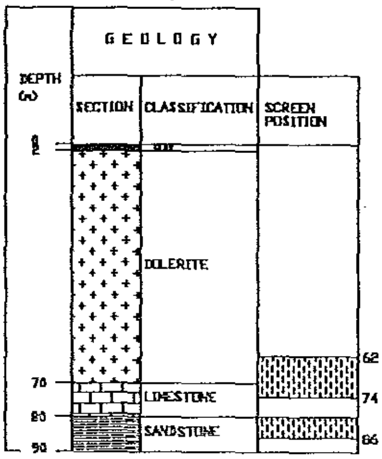
well label	Coordinates Northing Easting		Depth (m)	Static water level in (m)	Drawdown (m)	Aquifer thickness (m)	Pumping rate (l/s)	**Transimissivity (m^2/day)**	**Hydraulic conductivity (m/day)**	Aquifer Lithology
Airport 1	556406	1488604		22.45		14		**409**	**29.2**	Lmt /Dolerite
Airport 2	555787	1489875		8.65		18		**723**	**40.2**	Lmt /Dolerite
MTW-1						29.5		**29.2**	**0.99**	Shale/dolerite
TW-5	552880	1489018		16.02		28		**127**	**4.54**	Dol/SSt/ Lmt
TW-4	553140	1488452		16.93		19		**24.4**	**1.28**	Dolerite
Lesperance	551526	1487025			2.95	24	4	**27.4**	**1.14**	Dolerite/shale

Appendix 10. Results of pumping and recovery tests.

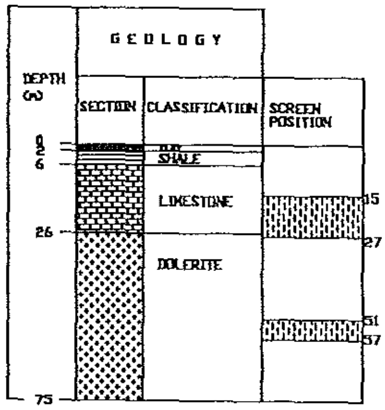
Rec. = recovery test result.

Appedix 12. Well Logs, after Wter Well Drilling Eterprise

Airport Well No.1



Airport Well No.2



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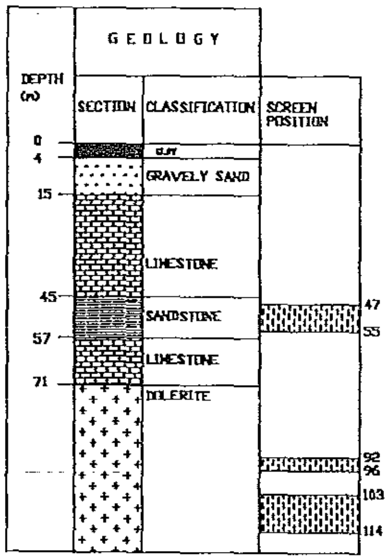

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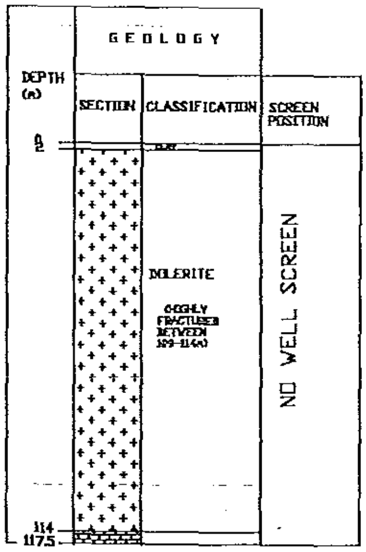

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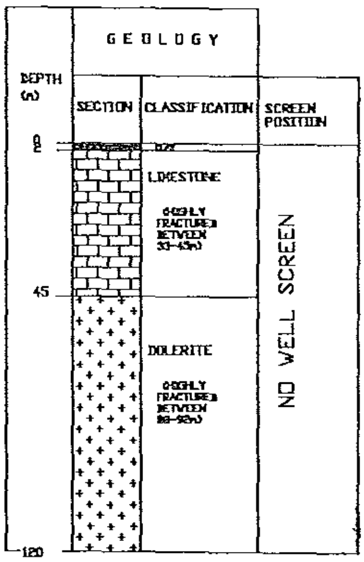

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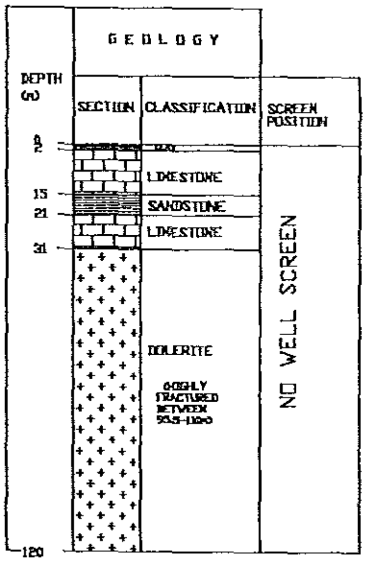


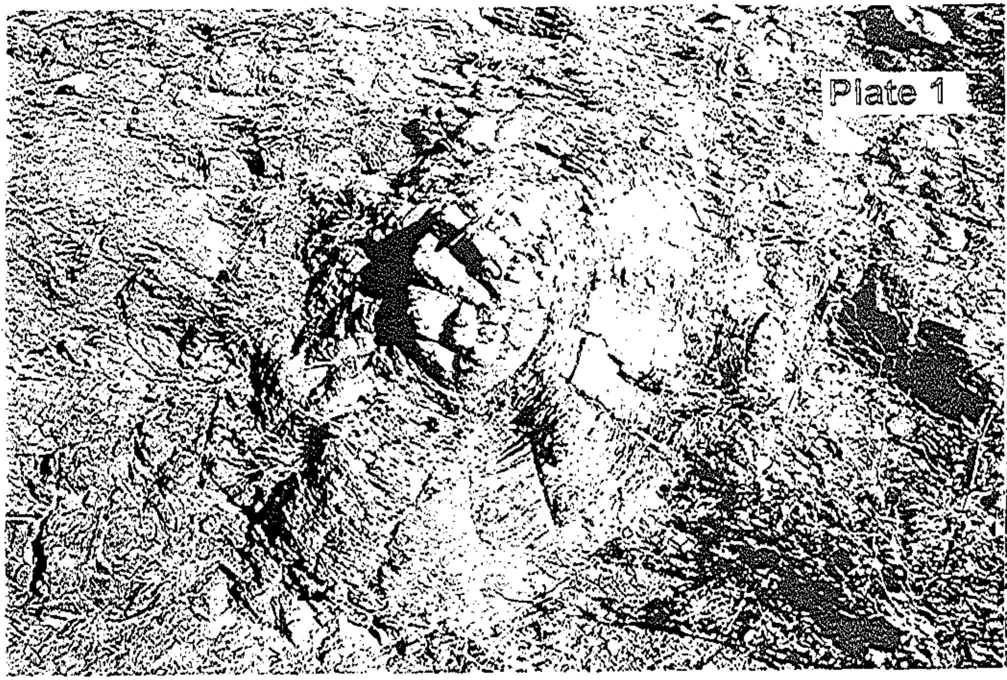


Plate 1


Plate 2

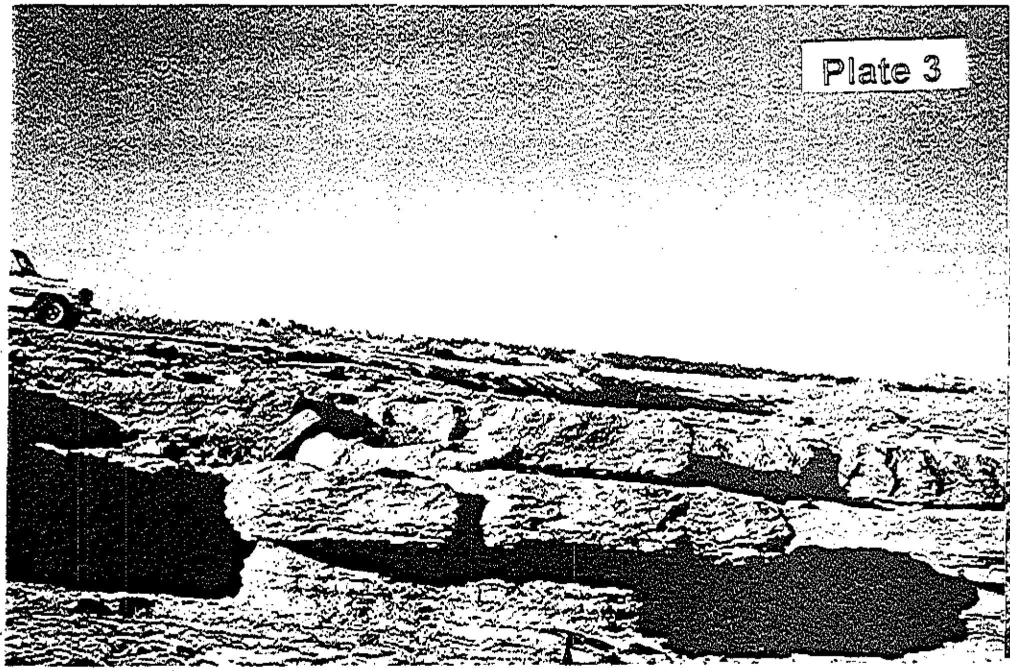
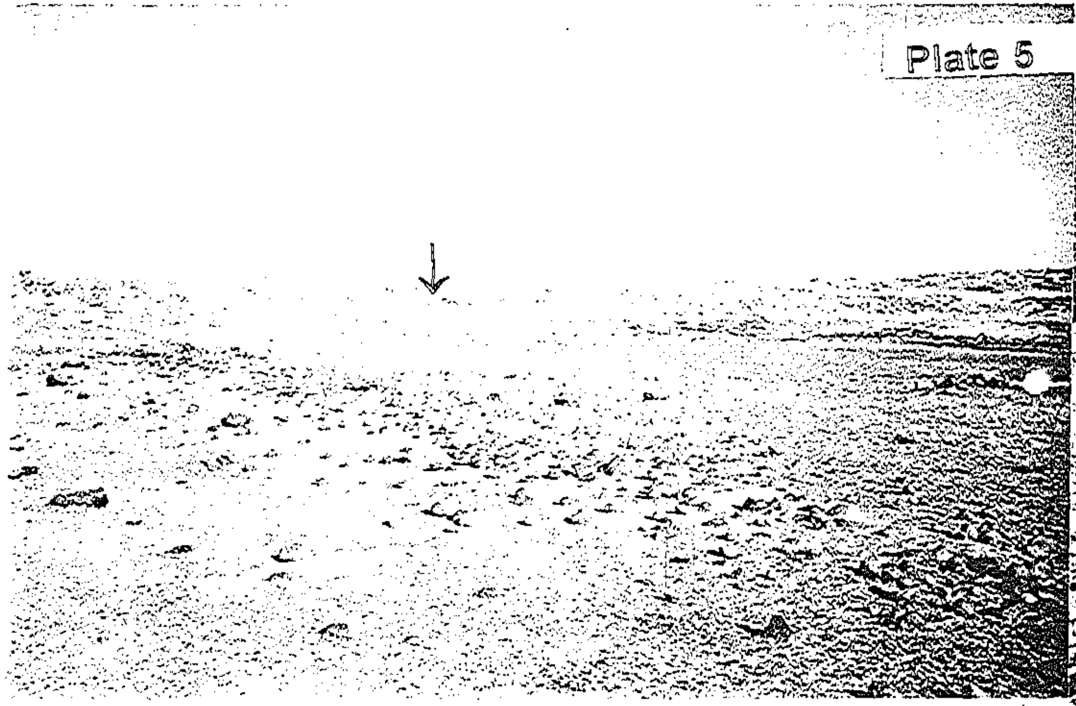


Plate 3


Plate 4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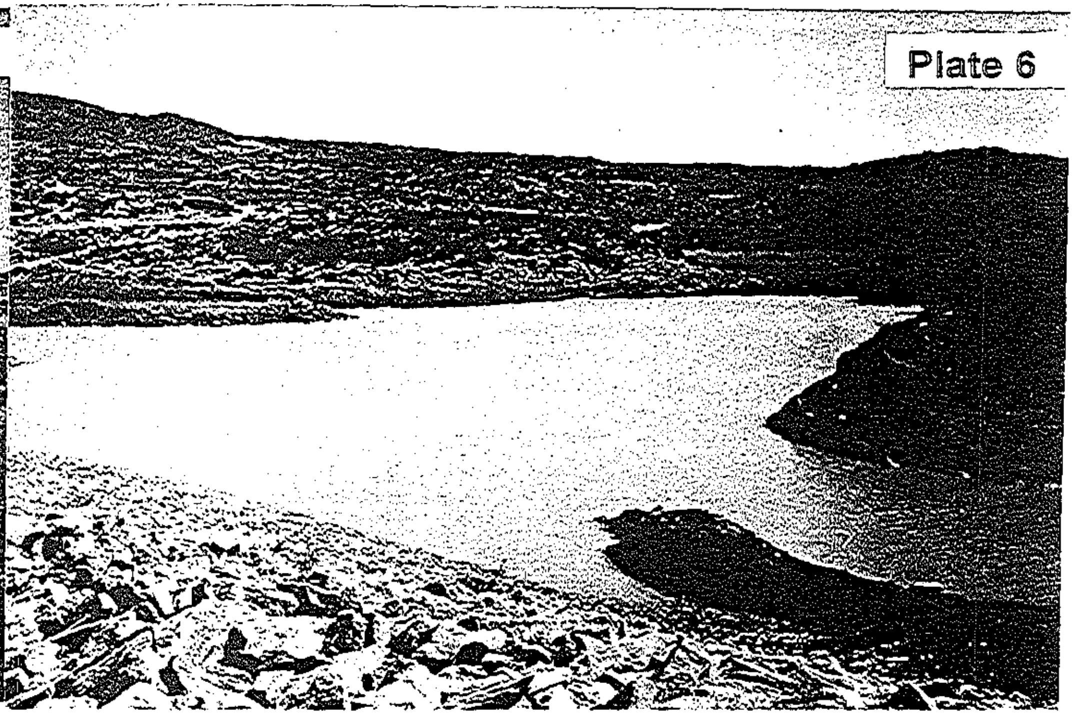
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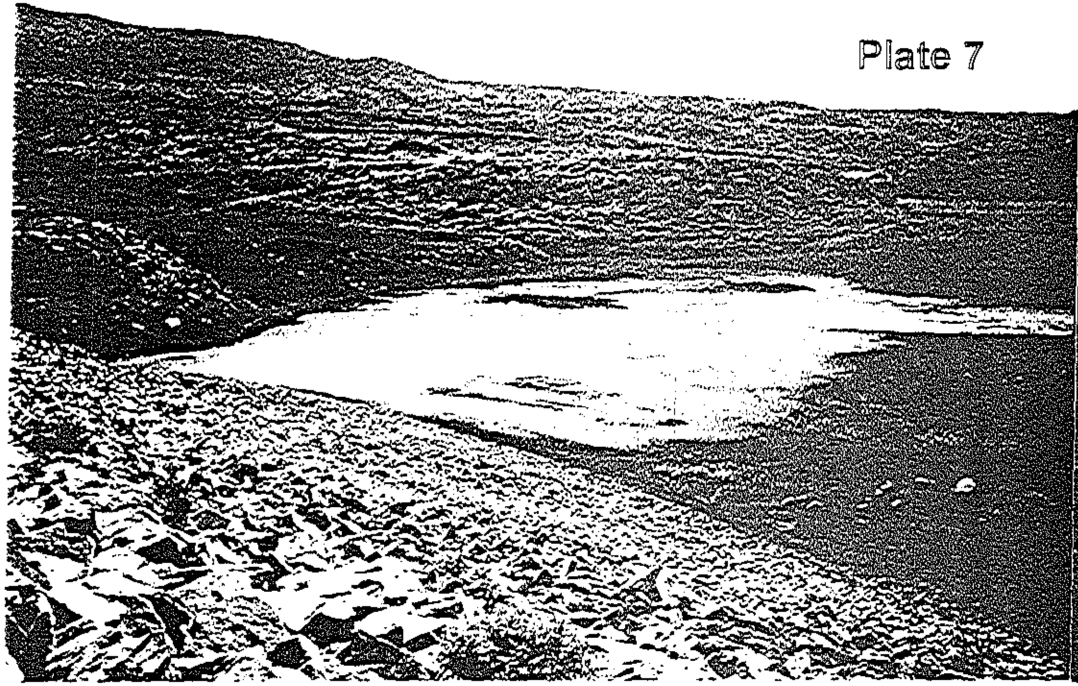
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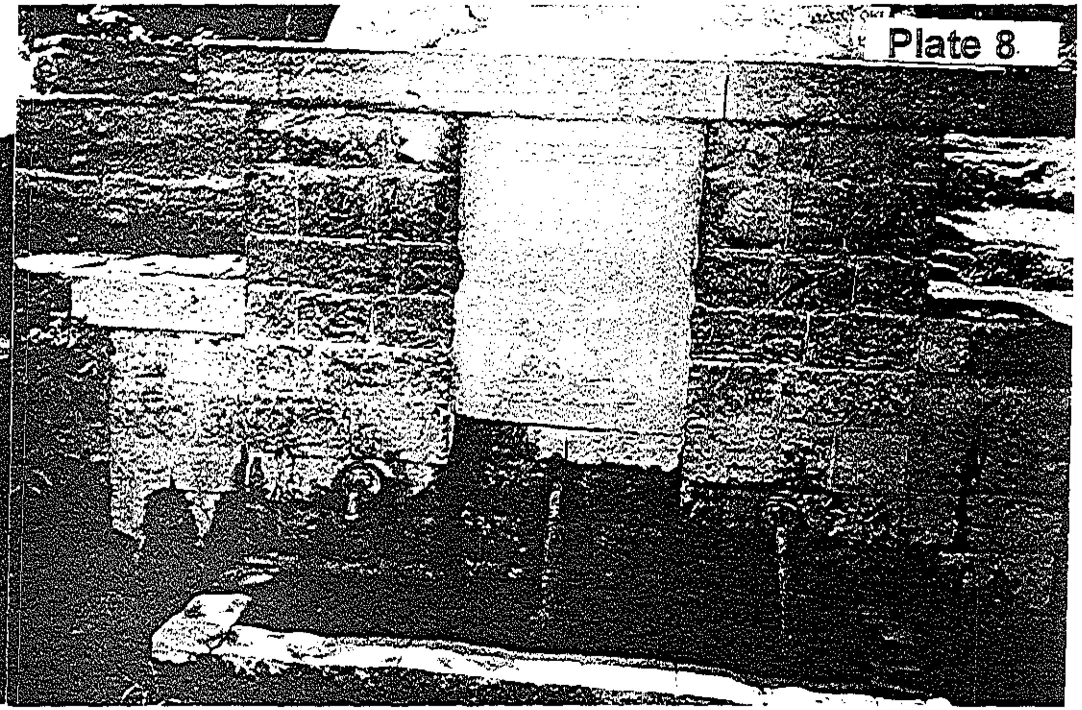
Plate 8