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HYDROGEOLOGY OF NAZRET

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ABSTRACT

The study area is found in the southern part of the northern sector of the Main Ethiopian Rift some 97 km southeast of the capital. It covers a surface area of about 370 sq.km.

Elevation varies from below 1600 m.a.s.l. to more than 1970 m.a.s.l.. More than 70% of the area represents low lying flat land with slopé of 1 to 10%.

The area is covered by various igneous rocks which are products of volcanism that spanned from Pliocene to Recent, and also by Quaternary sediments. The volcanics include; ignimbrites, basaltic flows, rhyolitic flows and domes, unwelded tuffs, pumice and ash deposits. Lacustrine sediments, alluvium and colluvium represent the non-volcanic deposits in the area.

Mean annual rainfall of 822.53 mm and mean annual temperature of 21°C characterize the study area. According to water balance study over the small sub-catchment at the centre of the area, generally about 49% of the mean annual rainfall is lost through evapotranspiration. While about 20% is available for runoff and the remaining about 30% is accounted for infiltration to the ground.

The main aquifers in the area are coarse grained lacustrine and alluvial sediments, pyroclastic rocks (cinders, volcanic sand and pumice), and weathered or fractured volcanic rocks mainly basalts and also sometimes ignimbrites.

From the pumping test data analyses, permeabilities and transmissivities of rocks have been found to vary from 0.50 to 78.50 m/d and 14.73 to 1355.20 m^2/d respectively. Specific

capacity also ranges from 0.26 to 9.13 $m^3/hr/m$. High permeability values are observed for the aquifers in the southern part of the area. The pumping test analyses also showed that there is a recharge from Awash river to the aquifers at Melka Hida well field.

Depth to groundwater level ranges from few meters in the southern part of the area to more than 170 meter in its northern part. From the groundwater contour, it can be observed that the general groundwater flow is to the south in the deeper aquifers. In the shallow aquifer zone (that is , southern part of the study area) groundwater flows towards Awash river in locally different directions from both sides of the river.

The chemical analyses result showed that the waters of the area are mainly bicarbonate type varying from sodium-bicarbonate to calcium-bicarbonate ones. The analyses also showed that there is high fluoride concentration above the acceptable limit for drinking in the groundwaters.

Potential places for groundwater in the area are restricted to its southern part. The remaining part is of limited potential not only due to low permeabilities of aquifers but also due to large depth to groundwater level.

Finally, it seems that conjunctive use of groundwater and surface water from Awash river is the only solution to meet future water demand of the town and of its surrounding.

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1. Introduction

1.1. Objective

It might be appropriate to say that water that could be used for various purposes (municipal, agricultural and industrial) is abundant in many areas in Ethiopia. But, it is the poor distribution and management together with lack of detailed water resources studies that largely create a problem.

The primary factor for the growth and development of a town is the availability and delivery of sufficient and good quality water supply to support present and future needs of the town and of its surrounding. This requires optimum development and utilization of the available surface and/or subsurface water resources in the area. Hence, the need for the detailed investigation of these resources goes without saying.

The study area includes the town of Nazret and about 25 peri-urban peasant villages. Nazret is one of the most important and fast growing town in the Rift with an existing population of more than 110,000 people (Nazret City Council, 1990). According to NUPI (1990) about 16,000 people reside in the 25 peri-urban villages. In the coming 20 years, the population of mainly the town and of its surrounding is expected to grow significantly. Projection (from a population of 108,000 in 1990, Nazret City Council) with a medium growth rate of 5% per annum (NUPI, 1990) gives a population of more than 280,000 in the year 2010 for the town of Nazret.

Nowadays, the area is almost entirely supplied by groundwater sources. However, there exists a water supply and quality problem in Nazret and its surrounding. The problem is particularly more serious in the surrounding peasant villages which, except in few cases, almost entirely bank on the water supply of the town.

There are about seven medium scale industries presently functioning together with a number of small ones in Nazret. It appears likely that the number of industries will increase in the future with increasing urbanization thereby rising the respective industrial demand.

From agricultural view point , there is no extensive irrigation practice in Nazret and its immediate vicinity except those few places along Awash River (southern extreme of the study area). The peasant population in the area fetches water, for domestic and cattle watering purposes, mainly from the water supply system of the town using animal back after travelling a long distance from home. However, this should not have to continue as it is now for the living condition of the farmers must be improved in this respect through the development of new wells near their villages and improving the standard of the water supply provision. It is also observed that the farmers in the area experience rain fed cultivation to produce food crops only once a year. The other important thing to the local farmers is, therefore, the changing of their farming scheme to irrigation based cultivation. But, again for this additional water supply from whatever source is mandatory.

In general, besides the already existing water supply problems in the area, there is a need for additional water sources of good quality and assuring quantity to support the ever increasing population. Additional sources are also necessary to ensure increased supplies to meet future industrial and agricultural demands.

In the main, since the present supply of water for Nazret and its surrounding is obtained from groundwater and on top of this, since there are no perennial streams in the immediate vicinity of the town the importance of the groundwater resource and its respective detailed investigation to achieve optimal use is indispensable.

Therefore, the present study is meant to:

1) evaluate the groundwater potential of the area,

2) define major water bearing geological units that are permeable enough to yield economic quantities of water to wells in the area and map them in such a way that it helps to locate important groundwater reservoirs; in doing this: a) to give reasonable approximation of the water budget of the small urban sub-catchment of Nazret town, b) to establish physical parameters of aquifers like transmissivity, storage coefficient and specific yield for those wells with pumping test data, and c) to give more detailed view of the aquifers bordering Awash river (Melka Hida well field) and their relation with it,

3) evaluate the quality of waters in the area based on international standard quality requirements,

4) suggest water management of the area,

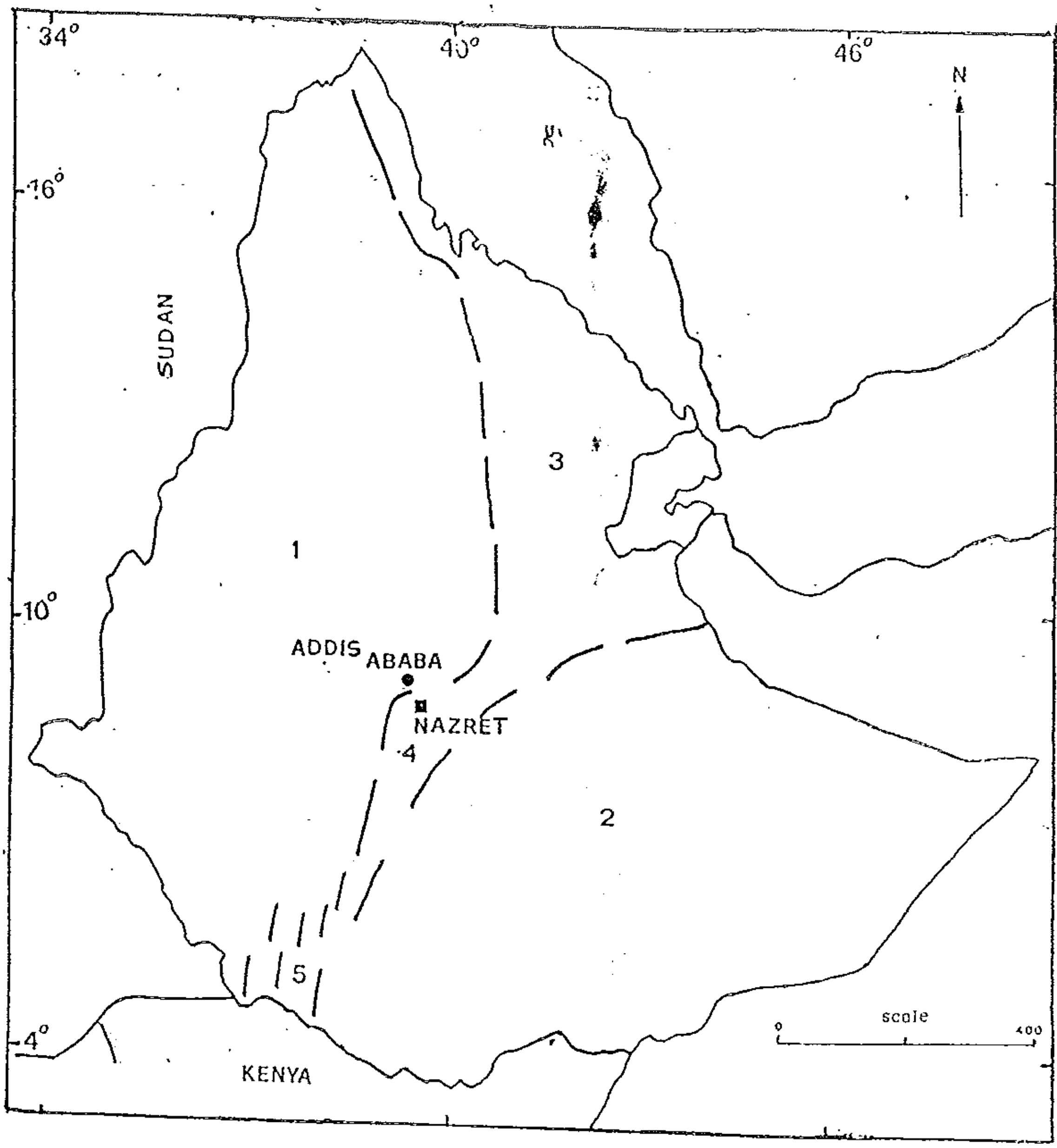
5) to see if conjunctive use of the groundwater and surface water from Awash river is necessary for the supply of the area, and finally,

6) identify and suggest water related problems which might need further closer look in the area.

1.2. Location and Extent

The investigated area is enclosed between 8 35'00"-8 36'46" latitude North and 39 11'57"-39 21'15" longitude East on the floor of the northern part of the Main Ethiopian Rift System. Nazret town which is found almost at the centre of the study area is located 97 km southeast of Addis Ababa along the main road to Asseb (fig.1.1). The area covers a total surface of 370 sq.km.

Nazret sub-catchment for which water balance study is conducted represents the central part of the investigated area and covers a surface of about 71.06 sq.km. This sub-catchment is mainly defined by geographic features and is surrounded by a number of other small local sub-catchments. It is bounded to the west and northwest by Kechema Ridge, to the east by Dibibisa Dome, to the southeast by Migira Dome and to the south by Boku Ridge. The northern boundary of the sub-catchment is not a conspicuous feature on the surface. It is given by a local water divide roughly 200 m south of the Mermersa seasonal stream.



1 = Western Ethiopian Plateau
2 = Southern Ethiopian Plateau
3 = Afar
4 = Main Ethiopian Rift
5 = Southern Rifts

Fig. 1.1. Location map.

1.3. Accessibility

The main road to Asseb passes through the study area dividing it into two almost equal parts. Nazret town which is found at the centre of the area is located along this road.

A number of both gravel covered roads and motorable tracks have cris-crossed the area. Hence, nearly every part of the study area, except the ridges and gorges, is accessible by a field vehicle.

1.4. Physiography and Drainage

The investigated area is found within the Wonji Fault Belt (Mohr, 1960) which is one of the main structural systems in the Ethiopia Rift and is characterized by generally NNE-SSW oriented faults forming minor grabens and horsts. The present physiography of the study area is, therefore, mainly the result of volcano-tectonic activities that occurred in the past and also deposition of sediments which are considered to be largely of fluvial and lacustrine origin. Hence, main landscape in the area include fault scarps, fault controlled depressions which are often covered with sediments, volcanic domes (usually elongated in the north-northeast direction) and volcanic cones.

Major proportion (more than 70%) of the area represents a relatively low lying flat land (1 to 10% slope). Elevation varies from around 1600 m.a.s.l. in the lowest parts of the area to more than 1970 m.a.s.l. on the Kechema Ridge (west of Nazret). Many other scarps, ridges and domes do also stand above the low lying land with significant elevation contrast.

Nazret town is located in a structural depression bound to the west by parallel strike scarps running in a NNE-SSW direction along main faults and to the east by north-northeast elongated ridges. It has an average elevation of 1620 m.a.s.l..

A generally parallel (and sometimes rectangular) drainage pattern characterizes the area mainly due to the NNE-SSW oriented faulting.

The area is drained by a number of different sized seasonal streams and gullies which usually start from the sides of the sloppy[1] scarps, ridges and domes. Most of these streams are wadi type and the drainage network is not generally well developed. They initially begin as rills and gullies on the slopes and progressively join to the main streams that have dissected the low lying flat land which ultimately feed Awash river. While some of the streams and gullies sink in the lower slopes within or outside of the study area. Awash is the only perennial river in the vicinity found at about 9 km to the south of Nazret.

The main streams have relatively wide and deep V-shaped valleys. In places they have cut down the whole thickness of the soft sediments. On the other hand, the smaller streams and gullies are characterized by narrow down cutting valleys which sometimes have nearly vertical walls. Most of them are non-graded.

The western and northern parts of the area contain relatively well developed drainage pattern. The western part is characterized by nearly parallel main streams, running NNE-SSW, that have short tributaries which start from the sides of the bounding ridges. The streams drain into Awash river. In the northern part of the area Mermersa is the main stream into

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[1] Slopes as high as 50% have been observed in places.

which seasonal water from the surrounding high lands drains. It flows mainly to the east and later it drains into a swamp northwest of the study area. A rectangular drainage pattern is shown by Mermersa main stream in this part of the area.

Drainage in the eastern and southeastern parts of the area is not mostly well developed. Many streams and gullies which are usually non-graded sink into the loose deposits in the low lands. Particularly those small streams that emanate from the eastern side of Dibibisa dome sink into the sediments along a north-northeast line giving a probable alignment of a buried fault or fracture zone.

In the Nazret sub-catchment almost all runoff from the surrounding high slopes drain into Nazret town causing flash floods during large storms. There is an artificially developed drainage way which serves as the only outlet from the sub-catchment and that joins Awash during large storms.

There seems to be a relationship between the main stream courses and the geologic structures (faults and fractures) in the area. This is evidenced by the nearly parallel streams in the western part and by the offset in the channels of Awash (up stream of Melka Hida Well Field) and Mermersa (north of Nazret).

1.5. Climate and Vegetation

The study area is characterized by a generally warm climate with a mean annual temperature of 21 C and mean annual rainfall of 822 mm. It is classified as semi-humid to semi-arid environment (Upper Kola) which mainly characterizes the altitude range between 1300 to 1800 m.a.s.l. and annual rainfall between 750 to 1000 mm (Axumawite, 1984).

There are only small diurnal and seasonal variations in temperature with mean annual maximum and minimum temperatures of 28°C and 14°C respectively. March, April and May represent the hottest months having maximum temperatures exceeding 31°C. While November is the coldest month with extreme minimum value reaching as low as 7.6°C.

There are no relative humidity records for Nazret. However, Table 1.1 depicts the relative humidity for Wonji which is the nearest station and it is believed that Nazret shows similar pattern.

Table 1.1. Relative Humidity (RH) at Wonji, in Percentage.

Month	J	F	M	A	M	J	J	A	S	O	N	D
RH	54.7	49.9	56.6	52	52.2	51.8	65	66.8	64.7	57.3	52.6	53.3

Like many other places found in the floor of the Main Ethiopian Rift, the annual potential evapotranspiration in this area exceeds the mean annual rainfall.

The area is extensively cultivated except in the deeply dissected, highly elevated and bed rock covered parts. Maize and "Teff", and pulses (haricot bean, lentil and chick-pea) are the dominant food crops being grown. Otherwise the area is generally devoid of abundant vegetal cover. It is characterized only by scarcely distributed acacia and scattered bushes. Other types of plants like Eucalyptus and Junipers occur very occasionally in few places. Isolated Ficus trees (Shola) occur mainly along Awash River. These Ficus trees are phreatophytes to the shallow aquifers occurring adjacent to the Awash river.

1.6. Previous Works

Several publications on the geology and tectonic development of the Main Ethiopian Rift in general and its northern sector in particular, which could significantly contribute to a better understanding of the study area , have been produced in the past. Of these, those of Di Paola (1972), Kazmin and Seifemichael (1978) and of Alula (1990) are of specific interest. Di Paola gave an overall account of the geology and stratigraphy of the volcanics (and sediments) in the area enclosed between 7°00′ and 8°40′ latitude North in the Rift. Kazmin and Seifemichael considered aspects of geology, stratigraphy and tectonic development of Nazret area and prepared geologic map (Nazret Sheet NC 37-15) in a scale of 1:250,000. Alula, in discussing structure and tectonics of the area (Msc. thesis), specifically gave an account of the different rock units in Nazret area and lithologically mapped them in 1:50,000 scale. Other geologists in related aspects include: Bigazzi et al. (1981), Mohr (1967a, 1987), Meyer et al. (1975) and others.

Skutan et al. (1982) carried out resistivity survey (VES and Dipole-Dipole profiling) in two "lacustrine basins" near Nazret town, most part of one of which is included in the present study area. This work gave estimated thickness of the sediments and underlying volcanics along certain profile lines.

Aspects of water supply and sanitation of Nazret town was studied by GWE (1983) and recently by Devecon (1990). The former was a very brief account in this respect. While the later conducted an investigation for the WSSA[2] and examined water supply situation of Nazret town and its future demand. The work proposed a future water supply system and drew attention to the utilization of Awash River as an additional future supply source to the town.

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[2] Water Supply and Sewerage Authority.

The only hydrogeological work in the area is that of Getahun (1985) which is the Hydrogeological Map of Nazret Area (Sheet NC 37-15) in 1:250,000 scale. This work gave a minor account of the local hydrogeology of the area and regionally classified the rocks of the area in to different permeability groups. Other related work also include, the drilling and pumping report on some wells at Melka Hida (south of Nazret) by Manhasebo and Yirga (1989).

1.7. Methodological Approach

The project work was basically started in the office by reviewing available literatures on different aspects of the area which were relevant to the research. This was accompanied by aerial photo and topographic map interpretation in the laboratory as a preview to the field investigation.

The geological field investigation carried out was aimed to identify and map the various lithologic units occurring in the study area, thereby also studying geologic structures, topography, drainage and other aspects. The time stratigraphic relation to each other of the different rock units and their regional correlation was also established on the basis of field investigation, available absolute age determination data and previous works. Then after, the area was lithologically mapped in 1:25,000 scale based on an integrated incorporation of field data and the laboratory interpretation. Selected rock samples have been collected, in the course of the geological field work, for thin-sections and later studied under petrographic microscope.

Following .and simultaneously with the geologic investigation, detailed hydrogeological (and hydrological) studies were conducted. These again started by first collecting available hydrogeological data of the study area in the office and later in the field. In the main, the study area was hydrogeologically treated as follows:

a) The different rock units which were identified and mapped were later grouped and also mapped according to their permeability (mainly qualitatively). While doing this, the lithologic map was used as a basis for preparing hydrogeologic map of the same scale.

b) The fundamental hydrologic parameters, i.e., precipitation, evapotranspiration, runoff and infiltration over the study area were investigated as thoroughly as possible. This includes interpretation and also determination of some of the parameters. Water balance study was particularly conducted over, a delineated, small urban sub-catchment which represents the central part of the study area enclosing Nazret town. This was done by the help of the Balance Equation :

$$P = E + R + I$$

Where, P = precipitation; E = Evapotranspiration; R = Runoff and I = Infiltration (all in mm).

c) Characterization of physical and chemical properties of groundwater and surface water (Awash River) of the study area with laboratory analysis (done at the laboratory of WSSA, Central Region) on the basis of already established international quality standards for various purposes (municipal, industrial and agricultural).

In the course of fulfilling the above main tasks, other important hydrogeologically relevant works have also been carried out. These include: bore and hand dug well inventory together with phreatimeteric measurements which helped in the construction of piezometric contour lines; identification of hydrogeologic basins which are, of course, complicated by the geologic structures mainly faults; establishment of aquifer characteristics K, T and S for those wells with pumping test and log data; and evaluation of the general condition of the area in terms of groundwater resource potential.

2. Geology of the Study Area

2.1. Regional Geology

The Ethiopian rift system which is part of the East African Rift system may be sub-divided into three main sectors. These are: the South Western Rift Zone, the Main Ethiopian Rift, and Afar.

The Main Ethiopian Rift (MER) is a symmetrical graben with uplifted flanks and steep border faults (Gidey et al., 1990). This structural depression serves as a divide between the northwestern or Ethiopian plateau and the southeastern or Somalian plateau. According to many authors (Di Paola, 1972; Mohr, 1986; and others) this rift is the result of tensional movements which affected the uplifted Ethio-Somalia plateau. A large number of step faults produced a total difference in altitude of more than 1000 m between the top of the plateaux and the floor of the rift. Almost all of these faults are normal faults (Di Paola, 1972)

The floor of the MER is marked by a persistent belt of intense, fresh, faulting which has been termed the Wonji Fault Belt (WFB) (Mohr, 1960). The WFB extends from South of lake Chamo in southern Ethiopia to the Lake Abhe area in central Afar.

Two main tectonic events have been recognized concerning the tectonic evolution of the Ethiopian Rift System. The first event which started since Eocene (Mohr, 1967a) involved the uplift of the Ethiopian swell. Large scale faulting later took place across the swell to form the Afar and the Ethiopian Rift and this represents the second major tectonic event. The initiation of the Ethiopian Rift and the Afar can be traced to

14 My ago (Kazmin and Seifemichael, 1978). Other authors (Barberi et al., 1975, and others) suggest an Early Miocene age for the rifts. The last major episode of rift faulting resulted in the formation of the Wonji Fault Belt which is constituted by a number of faults which shattered the rift floor into several relatively small horst and graben structures.

According to Gidey et al. (1990) the MER may be geographically sub-divided into three sectors: northern, central and southern. The study area is found within the floor of the northern sector of the Main Ethiopian Rift.

Di Paola (1972) identified four main successive periods of volcanic activity in the part of the MER found between 7°00′ and 8°40′ latitude north. Accordingly, the main events are:

1) basaltic eruptions with emplacement of explosive dominantly ignimbritic products and associated volcano tectonic collapses;

2) building of silicic central volcanoes on the ignimbrites;

3) basaltic fissure eruptions and

4) edification of recent silicic, mostly pantellertic, centres and associated "subhistorical" basaltic fissure eruptions.

Meyer et al., (1975) distinguished two main volcanic units in the northern part of the rift system. The first of these units is identified as "Nazret series[3]" with an age range of 5-2 my. According to Kazmin and Seifemichael (1978), this series includes a thick succession of ignimbrites, unwelded tuffs, ash

[3]The term "Series" was later replaced by "group" by Kazmin and Seifemichael (1978).

flows, rhyolite and trachyte flows. They form the large part of the rift floor and also outcrop in the rift escarpments and on the adjacent plateau margins. In Nazret area, according to Meyer et al. (1975), this series is represented by rhyolites and ignimbrites. Eruptions of these units is considered to be mainly through fissures and vents, but local centres also occur (Alula, 1990).

The second volcanic unit of Meyer et al. (1975), is the Young "Wonji series[4]" built up mainly from extensive basaltic flows. Ignimbrites, rhyolite and trachyte flows, and pumice deposits are also found in this series. This volcanism is spatially restricted to the axial extension zone of the rift system which is the WFB. The volcanic products of this series are observed to be associated to NNE-SSE running faults or are erupted from fissures and vents in this direction (Alula, 1990). The Wonji volcanism spanned from Pleistocene up to Recent, according to several authors. In the Nazret area this series is mainly represented by basaltic and rhyolitic lava flows.

The Nazret and Wonji volcanic units are separated by a major episode of rift faulting. This faulting phase came into activity 1.6-1.8 my ago (Kazmin and Seifemichael ,1978; Mohr, 1986)

The stratigraphic sequence of the various volcanic products in the northern part of the MER and adjacent plateaus which have been emplaced since Eocene to Recent has been reconstructed by Di Paola, 1972, as depicted in Table 2.1.

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[4] The term "series" was later replaced by "group" by kazmin and Seifemichael (1978).

Table 2.1. Stratigraphic sequence of the various volcanic products in the northern part of the MER, after Di Paola.

UNIT	AGE
Alluvium and lacustrine sediments	Recent to Pleistocene
Recent alkaline and peralkaline rhyolitic pumice, ashes and obsidian lava flows	Holocene
Alkali trachytic lava flows and domes	Recent to Pliocene
Recent basaltic lava flows and spatter cones	Recent to Pleistocene
Basaltic hyaloclastites	Recent to Pleistocene
Old alkaline and per alkaline rhyolitic lava flows and domes, associated pumice and ashes	Early Pleistocene to Late Pliocene
Alkaline and peralkaline ignimbrite associated to pumice and ashes and lahars (mud flows)	Pliocene
Tertiary basalts and ignimbrites of the plateau Trap Series	Pliocene to Early Eocene

The general volcanotectonic history of the northern part of the MER has been reviewed and summarized by Mohr(1986) as follows:

21-18 My	Broad crustal down warping and fissure basalt in northern part of the rift, local rifting developed in the south.
15-13.5 My	Warping and initial faulting of northern rift margins.
10-7 My	Faulting and fissure basalt extrusion
5-3.5 My	Faulting and massive silicic eruptions specially in the north.
1.8-1.5 My	Rift margin and floor faulting.
1.0-0.9 My	Eastern margin faulting and plateau uplift.
0.25-0 My	Development of the Wonji fault belt.

2.2. Geology

2.2.1. Stratigraphy

It has been tried to reconstruct the composite stratigraphy of the area based mainly on lithologic correlation aided by available absolute age determination data and previous works. Sections were found along faults, stream cuts and in quarries. Well sections have also been considered. Correlation among sections was a difficult business for many outcrops are discontinuous and due to the abundance of several small and apparently local units (mainly pyroclastic deposits).

The oldest volcanic rocks present in the area are represented by compact fiamme ignimbrite (I_1) which shows a contemporaneous emplacement with alternating flows of aphanitic dark basalt (B_1). From sections observed in other places around the study area and from previous works, the I_1 unit is believed to be relatively older than the B_1. These rocks are prominently exposed along north-northeast oriented faults in the area west and southwest of Nazret town. An absolute age of 1.7 My was given to the ignimbrite unit (Mohr, 1987).

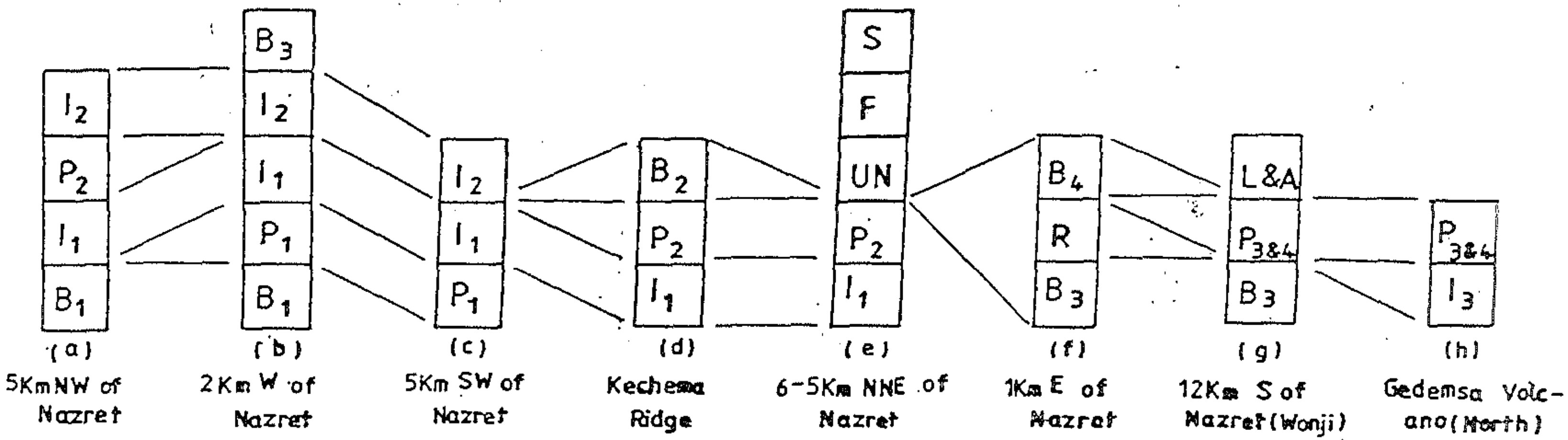
Thin and subordinate layers of pyroclastic pumice fall and ash flow deposits have often been observed in sections occurring as interlayerings between main flows in the above units. These pumice fall and ash flow deposits do also outcrop in few places.

The above sequence is followed by rhyolitic lava flows (R_1) which mainly formed the Boku Ridge and are often associated with thin obsidian interlayerings. They have also been observed to contain thin ash flow and pumice layers in some places. It was very difficult to get best exposed section that reveals the stratigraphic position relative to other units of these flows. However, from absolute age data and from previous works it is believed that they are younger than the above units. An absolute age as old as 0.8 my and younger has been assigned to these rocks (Bigazzi, et al., 1981).

Then comes the poorly welded lithic rich ignimbrite (I_2) with absolute age of 0.51 my (Mohr, 1987). The coarsely porphyritic vesicular basalt unit (B_2) which is characterized by abundant feldspar and olivine phenocrysts take a stratigraphic position above the poorly welded lithic rich ignimbrite (I_2) unit. An absolute age of 0.4 my was assigned to this unit (Alula et al., 1992). This vesicular porphyritic basalt unit in turn takes a stratigraphic position below the acidic volcanics (R_2) that formed the rhyolitic domes northeast and southeast of Nazret, and flows east of it. A particular section just west of Nazret (along the main road to Asseb) shows a white rhyolitic flow, which is believed to belong to this unit, overlying a vesicular basalt flow. No absolute age data is available for these flows but they are generally considered to be of Holocene age (Di Paola, 1972). Then comes units that are products related to Gedemsa caldera. They are formed by ignimbrites, ash falls and flows, pumice falls, and surges listed in a stratigraphic sequence from bottom to top as is displayed by sections in the northern part of the caldera. An absolute age range from 0.8 my to 0.2 my has been assigned to the products related to Gedemsa (Bigazzi et al, 1981).

The last phase of volcanic activity in the study area is represented by unwelded tuffs and basaltic cinder (and spatter) cones. The later are associated with basaltic lava flows and an age younger than 0.06 My was given to them (Bigazzi et al, 1981).

Finally, the lacustrine and fluvial sediments represent the youngest deposit in the stratigraphic sequence. Their age spanned from Pleistocene up to the Present (Di Paola, 1972; Kazmin and Seifemichael, 1978). Table 2.2 shows the general stratigraphic sequence of the study area on the basis of lithologic correlation. Figure 2.1 shows locally exposed rock sections observed in different parts of the study area.



S	TOP SOIL
F	FLUVIAL SEDIMENTS (WITH GASTROPODS & RELLETS)
UN	UNWELDED TUFF (UNDERLAIN BY LEACHED SOIL)
L&A	LACUSTRINE & ALLUVIAL SEDIMENTS, SOIL
B_4	BASALTIC CINDERS & SPATTERS, SCORIAS & SCORIACEOUS BASALTS
$P_{3\&4}$	UPPER PUMICE & ASH DEPOSITS (WITH SURGES)
I_3	UPPER INTENSELY WELDED IGNIMBRITE (GREEN)
R	YOUNGER RHYOLITIC FLOW
B_3	PLAGIOCLASE PORPHYRY OLIVINE BASALTS
I_2	POORLY WELDED IGNIMBRITE
B_2	UPPER APHANITIC BASALT
P_2	MIDDLE PUMICE & ASH DEPOSITS
I_1	LOWER INTENSELY WELDED IGNIMBRITE (LIGHT GREEN)
P_1	LOWER PUMICE & ASH DEPOSITS
B_1	LOWER APHANTIC BASALT

FIG. 2.1. Locally Exposed Lithologic Units and Possible Stratigraphic Correlations (not to scale)

Table 2.2. Stratigraphic sequence of the study area.

Rock Unit	Symbol used in stra. sections	Age	Correlative unit
Lacustrine, alluvial and colluvial sediments.	L and A		
Unwelded Tuffs (with a dominant ash component)	UT		
Scoria and spatter products with associated basaltic lava flows	B_4	0.06 My (Bigazzi et al. ,1981)	Recent basalt of Kazmin et al. (1978)
Younger pyroclastic deposits (ignimbrite, pumice, ash, surge)	I_3, P_3, P_4	0.2 My and older (Bigazzi et al., 1981)	Gedemsa unit of Alula et al. (1992)
Younger rhyolitic lava flows and associated obsidian layers	R_2		Pantelleritic volcanics of Kazmin et al. (1978)
Plagioclase porphyritic olivine basalt	B_3	0.4 My (Alula et al., 1992)	Wolenchiti basalts of Meyer et al. (1975), Bofa basalts of Kazmin et al. (1978)
Poorly welded lithic rich ignimbrite	I_2	0.51 My (Mohr, 1987)	
Older rhyolitic flows & ass. obsidian layers (with pumice & ash horizons)	R_1		Older alkaline & peralkaline rhyolitic lava flows of Di Paola (1972) and others
Older pumice & ash deposits (with paleosoil horizons)	P_1 and P_2		Nazret group of Meyer (1975), Kazmin et al. (1978)
Aphanitic basalt	B_1 and B_2		Nazret group of Meyer (1975), Kazmin et al. (1978)
Intensely welded ignimbrite	I_1	1.7 My (Mohr, 1987)	Nazret group of Meyer (1975) Kazmin et al. (1978)

2.2.2. Lithologic description

In the study area reasonably good outcrops are found along ridges and escarpments (in many cases bound by faults), across road cuts, river cuts and in quarries.

The rocks exposed in the area consist of various volcanics and younger sediments. The volcanics vary from basalt to rhyolite in lithology and include basaltic flows,basaltic cinder and spatter products (forming cones), acidic lava flows and ignimbrites as well as pyroclastic flows and falls (mainly pumice and ash deposits). These rocks are products of rift volcanism that spanned from Pliocene to Recent (Mohr, 1987 and others). While the sediments (which are lacustrine and fluvial) are of Quaternary age (Kazmin and Seifemichael, 1978; Di Paola, 1972); the fluvial sediments being present day deposits.

The rocks outcropping in the study area have been put into six units mainly based on lithologic variations, though in some cases (pyroclastic deposits) relative age relation was also considered. These lithologic units are:

a) older pyroclastic deposits: which include poorly to intensely welded ignimbrites, ash flows and pumice fall deposits;

b) basic lava flows (basalts): consisting of an older aphanitic basalt flow and younger porphyritic vesicular basalts;

c) acidic lava flows: consisting of older acidic lava flows which form the Boku Ridge (south of Nazret) and other younger acidic products which mainly form elongated domes northeast and southeast of Nazret;

d) younger pyroclastic deposits: which include ash flows and falls, pumice falls, ignimbrites and surge deposits which are products of the Gedemsa central volcano together with much younger unwelded tuff which usually occurs in many topographically low lying places;

e) basaltic cinder and spatter products which form volcanic cones and associated basaltic lava flows; and finally

f) reworked volcanics, lacustrine sediments, colluvium and alluvium sediments.

2.2.2.1. Older intensely welded ignimbrite (I_I)

This unit represents the lowest and probably the oldest exposed lithology in the study area.It is mainly exposed along north-northeast oriented major normal faults forming steep scarps west of Nazret. Other outcrops are found north-northeast (Mermersa) and southwest (Melka Hida) of the town again along similarly oriented normal faults.

The ignimbrite is generally characterized by light green colour, dense welding, and contain abundant fiamme up to 20 cm in size. Exposed thickness varies from few meters up to more than 80 m (west of Nazret). The ignimbrite layer displays clear variation from top to bottom. The basal portion is less welded and contains relatively abundant lithic fragments. The middle portion on the other hand, is massive, densely welded and is characterized by the occurrence of well developed fiamme and lesser amount of lithic fragments. The upper part of the ignimbrite is again less welded, with patches of glass and pumice clasts and contains relatively abundant lithics. The lithics in the ignimbrite are dominantly silicic fragments and reach a maximum size of 3 cm.

Thin-section study of the upper portion of this unit shows an ignimbrite with incipient welding and partly developed eutaxtic texture. Constituent crystals consist of alkali feldspar, quartz, few hornblende and pyroxene. The matrix is made up of glass shards, tiny crystals and collapsed pumice (having cavity walls encrusted with minute crystals). The lithic fragments present are basaltic and silicic almost in equal proportion. A thin-section from the middle portion of this unit shows intense welding and eutaxtic texture. The mineral association includes abundant alkali feldspar, quartz, hornblende and scarce pyroxene set in a matrix made up of glass shards, collapsed pumice and small crystals. The lithic fragments present are mainly silicic.

A well developed columnar jointing is shown by the intensely welded middle portion of this unit. At places, joints with aperture width reaching up to 20 cm have been observed. West of Nazret, basalt flows have been observed as interlayers within this ignimbrite unit. In other places the unit is overlain by a poorly-welded coarse lithic rich ignimbrite (I_2) unit. The age of the fiamme ignimbrite unit has been dated to be 1.7 My (Mohr, 1987).

2.2.2.2. Aphanitic Basalt (B_1 & B_2)

These flows have been observed within and overlying the welded ignimbrite unit and are characterized by aphanitic fabric with scarce vesicles and carrying few phenocrysts. They are mainly exposed on the top of the Kechema Ridge (also named as Adama horst), bounded by NNE-SSW trending normal faults, west of Nazret. Other outcrops have been observed at the floor of Kimbibit river and along a scarp just west of the town. Outcrops with clear lamination structures and also with intense weathering and fracturing have been observed in places. The unit attains an observed average thickness of up to 30 m.

Petrographically the rock is fine grained basalt containing very small amounts (less than 2%) of phenocrysts of plagioclase and fewer olivine together in a microcrystalline groundmass. The groundmass is constituted by plagioclase lath, olivine grains which are usually marginally or fully altered to iddingsite, pyroxene and abundant opaques. Calcite occurs as a secondary mineral filling vesicles.

No absolute age determination is available for these basalt flows. However, from field relations (i.e, alternating thick flows in the above unit), a similar age as the fiamme ignimbrite unit (I_1) could be anticipated. The absolute age of this ignimbrite, as previously mentioned, has been determined to be 1.7 my (Mohr, 1987).

2.2.2.3. Older pumice and ash deposits (P_1 & P_2)

This unit, which is believed to have about similar age as the above two units (field relation), is constituted by pumice falls and ash flows which are often associated with paleosoil horizons. Main outcrops are found west and southwest of Nazret. They are generally best exposed in quarries and at the base of fault scarps.

The pumice fall deposits are characterized by coarse grained irregular shaped pumice clasts which are dominantly of lapilli size. Deposits contain pisolites in places and are usually associated with the ash flow sheets.

The ash flows have been observed in many sections as a separating layer between the ignimbrite deposit and aphanitic basalt flows (usually as thin ash levels). They are often associated with paleosoils and are also sometimes found as intercalations in the pumice fall deposits. Layer thicknesses do not exceed two meters in the field.

At places, thin layers (less than one meter) of ignimbrite have been observed associated with these pumice fall and ash flow deposits.

2.2.2.4. Older acidic lava flows (R_l)

Older acidic volcanics which occur as lava flows form the Boku Ridge (south of Nazret) in the study area. The flows mainly constitute white rhyolitic unit which is often associated with obsidian layers. Occasional layers of pumice and ash have also been observed. Phenocrysts are scarce in many rhyolitic samples taken from different parts of the ridge, and if abundant are difficult to identify in hand specimen mainly due to alteration and also due to their small size. The thickness of the flows in this area is estimated to be more than 100 m. Flow structures like banding and folding are evident in these rhyolites.

Petrographic study of representative samples from the rhyolitic flows of Boku Ridge reveal that the rocks are generally scarcely porphyritic with glassy to microcrystalline (sometimes cryptocrystalline) felsic groundmass which occasionally contains microlites of alkali feldspar. Phenocrysts are mainly alkali feldspar, quartz and rare aegrine. Flow structures are also evident in some thin-sections.

No clear field evidence could be observed to ascertain the relative position and relation between other lithologic units in the area and the acidic flows of Boku Ridge. However, data from Beggazi et al. (1981) indicates an absolute age of about 0.8 my and younger for these flows.

2.2.2.5. Lithic rich ignimbrite (I_2)

This is a poorly-welded, light yellow, coarse pumiceous ignimbrite characterized by abundant lithic fragments which are randomly distributed throughout the rock mass. It is mainly exposed in the area about 4 km west of Nazret and usually occupies relatively lower topographic levels. Other patchy outcrops are found to the northwest and southeast of the town. The size of the lithics reach up to 5 cm and that of the pumice clasts up to 12 cm. The lithics are mainly basaltic (sometimes scoriaceous) and silicic.

Thickness of the layer varies from few meters observed along stream cuts and gullies up to more than 25-30 m (exposed about 7 km west of the town along the Addis Ababa-Nazret road).

Petrographic examination confirms that the ignimbrite represents a scarcely welded rock with abundant lithics and pumice clasts. The lithics, which are basaltic and trachytic, themselves contain microcrystals of quartz, plagioclase, alkali feldspar and pyroxene. Crystal components present include alkali feldspar, quartz, green hornblende and rare pyroxene and are set in a partly eutaxtic matrix constituted by glass shards, collapsed pumice and tiny crystals.

This ignimbrite is observed to overly the fiamme ignimbrite west of Nazret and overlain by a porphyritic vesicular basalt flow (B_3). The lithic rich ignimbrite has been given an absolute (k/Ar) age of 0.51 my (Mohr, 1987).

2.2.2.6. Porphyritic basalt (B_3)

This unit generally consists of coarsely porphyritic vesicular basaltic flows mainly exposed along north-northeast south-southwest oriented normal faults forming small ridges.

Rocks of this unit carry abundant phenocrysts (up to 20%) of plagioclase and olivine (the former being more abundant in many samples). These phenocrysts are randomly distributed throughout the basaltic rocks and show considerable variation in amount and size from outcrop to outcrop. Phenocrysts of plagioclase which attain sizes as large as 2 cm have been observed in some outcrops. The amount and size of vesicles are also considerably variable.

The overall exposed thickness of the basaltic flows varies from less than a meter (near Wonji town) up to 10 m just south of Nazret. These porphyritic vesicular basalts are fractured and weathered at places.

Most of these flows are believed to be fissure eruptions, although, probable point source (central vents) could be inferred to some outcrops.

Petrographic examination points that these flows generally contain abundant (5 to 20%) phenocrysts of plagioclase, euhedral olivine (which often shows corroded outline and iddingsite rim) and augite. These phenocrysts are generally set in a matrix consisting of plagioclase lath, augite and olivine granules, and abundant opaque minerals (Fe-Ti oxides). Moreover, there is a variation in the phenocryst/groundmass ratio and to some extent in mineralogy among samples taken from different outcrops. The groundmass generally varies from microcrystalline to partly glassy. The size and relative proportion of phenocrysts do also vary significantly. Samples range from plagioclase porphyritic to olivine porphyritic basalt.

From field observation, it can been seen that these porphyritic vesicular basalts are relatively younger than the aphanitic basalt unit(B_1) described in a previous section. An absolute age of 0.4 My has been assigned to these porphyritic vesicular basalts (Alula, et al., 1992).

2.2.2.7. Younger acidic flows (domes) (R_2)

Younger acidic volcanics in the area occur as typical dome-forming flows and lava outpourings. The domes appear to be slightly elongated along north-northeast direction. Rocks generally consist of white crystalline rhyolites which are often associated with dark coloured obsidian interlayerings. Localities where main outcrops are found include: northeast (Dibibissa Dome), east (Migira Dome) and southeast (Wogillo) of Nazret. The rhyolitic rocks in these localities are fresh and slightly affected by significant faulting, contrary to the older acidic flows at Boku which are intensely dissected by major normal faults. The younger acidic flows reach up to 40 m in overall thickness. Flow structures are also evident sometimes.

Thin-section study of a sample taken from Dibibisa Dome shows a porphyritic texture with phenocrysts of alkali feldspar, quartz, hornblende and aegrine in a glassy to microcrystalline felsic groundmass containing some opaque minerals. The percentage of Phenocrysts to the groundmass ranges from less than 1% up to 5% in this and other samples.

The stratigraphic position of these acidic flows is not well established and no absolute age determination is available for the rocks. But just east of Nazret (along the main road) a rhyolitic flow which is considered to belong to this unit has been observed overlying the porphyritic basalt unit. Di paola (1972), Kazmin and Seifemichael (1978), and Getahun (1985) considered the rhyolitic domes northeast and southeast of Nazret to be relatively younger (of Recent age) than the flows further south at Boku.

2.2.2.8. Younger pyroclastic deposits (I_3,P_3 and P_4)

This unit consists of ignimbrites, ash flows and falls, surge, and pumice fall deposits, all belonging to the products of the volcanism associated with Gedemsa centre. The much younger unwelded tuffs are also included here. The ignimbrites and ash fall (and flow) deposits are not intensively outcropping in the study area but further south mainly east of the Wonji Sugar Estate. The surge and pumice fall deposits outcrop in the area south of Nazret around Wonji Kuriftu village. From their occurrence within the floor of the caldera, these pumice fall and surge deposits are considered to be post caldera products of Gedemsa volcanism (Alula, et al., 1992)

The pumice fall deposit, which in the area is associated with pyroclastic surges, is characterized by angular pumice clasts that rarely exceed lapilli size. The fall layer mantles small hills in the outcrop area and its thickness reaches up to 10 m.

A poorly sorted light grey surge deposit has been observed at an outcrop about 8 km south of Nazret. The thickness of this deposit is more than 3 m. Contained clasts do not exceed lapilli size and ash is the dominant component. The deposit displays a planar stratification and it overlies the above described pumice fall deposit that blankets the outcrop area. Unwelded tuff, which is dominantly containing ash components, is widely distributed in the area and occupies mainly lower slopes at Nazret and to the north, east and south of it. The tuff usually form different layers separated by paleosoils, colluvium or alluvium as can be clearly observed in many sections along stream cuts. Individual layers vary from as small as 30 cm up to 5 m.

2.2.2.9. Basaltic pyroclastics and lava flows (Cinder and spatter products forming cones with associated basaltic lava flows) (B_4)

Cinder and spatter products of basaltic composition (scoria and scoriaceous basalts) are abundantly distributed in the form of cones in the study area. These cones mainly occur southeast and southwest (around Wonji) of Nazret town. They are preferentially distributed along north-northeast oriented narrow zone, commonly known as the Wonji Fault Belt (Mohr, 1960). The cones are constructed around central vents, and show clear alignments along young fissures (faults).

At places, these cones are associated with basaltic lava flows. The flows mainly represent a very dark vesicular poorly porphyritic basalt. A petrographic study of a sample taken from a basaltic flow at Awash Melkasa Bridge (in the vicinity of the study area) shows that it is characterized by a vesicular, dominantly microporphyritic texture containing small phenocrysts of plagioclase, rare augite and rare alkali feldspar together with abundant euhedral olivine. The phenocrysts lie in a microcrystalline groundmass of plagioclase lath (and needles), granules of augite, olivine and abundant opaques. Olivine phenocrysts are fresh and occasionally occur in clusters sometimes with plagioclase and augite. The percentage of phenocrysts in thin-section is about 5 to 10%.

At many places, it has been observed that these cones and associated lava lie on the porphyritic vesicular basalt flow (B_3). The cones are often well preserved implying a younger age. Di paola (1972) considers these spatter and cinder cones and the associated flows to be of Pleistocene to Recent age. Bigazzi et al (1981) have obtained an absolute age younger than 0.06 My for these products. Some workers have noted the presence of much younger cones that could belong to recent historical times.

2.2.2.10. Recent Lacustrine, Alluvial and Colluvial Sediments

This group includes recent lacustrine, alluvial and colluvial (L,A and C) sediments which represent the only non-volcanic deposits in the study area.

Lacustrine sediments in the area cover almost the entire low-lying flat land at Wonji and its surrounding. The sediments are poorly consolidated and are moderately grained deposits of mainly silt and sand. Gravels, however, are not completely absent especially at depth as revealed by well log data. The lacustrine sediments also contain reworked volcanic materials of different size. They are often intercalated with thin (only occasionally exceeding one meter) horizons of tuff, pumice and various pyroclastic materials.

Lacustrine sediments in the study area attain thickness that varies from few meters up to more than 30 meters.

According to resistivity survey of Skutan et al. (1982), places with greater thicknesses of lacustrine sediments (along a profile) in the area are associated with down thrown sides of buried normal faults. However, no systematic variation in thickness could possibly be anticipated over the entire study area.

A lacustrine diatomite deposit with an exposed thickness of about 10 m is outcropping in the area at the back of kuriftu feed lot near Awash river. It covers an approximate surface area of 0.5 sq.km.

At Wonji the sediments are underlain by various pyroclastic deposits and/or basalt flows. The age of these lacustrine deposits is given to be Holocene (Di paola, 1972) and are believed to have been deposited in a lake which occupied this place during this time.

Fluvial deposits are common features in the Awash river bed and associated flood plains, and along the channels of Mermersa and other small ephemeral streams.

Although Awash is not at a well developed meandering stage in this area, the fluvial deposits developed and their settings can be considered as that of a meandering system. Alluvial deposits in the Awash river are mainly formed in the river channel and the associated flood plain. The flood plain in this area is mainly swampy particularly in the part which lies down stream of the Wonji Bridge (south of Boku ridge). Sediments outcropping in the flood plain are mainly fine grained (clays and silts) which represent levee and flood basin deposits.

From well log data in Melka Hida area, a vertical variation in grain size have been noted and this indicate a pattern of change that corresponds to a meandering system. However, this generally fining upward sequence is complicated by intercalations of various pyroclastic materials mainly tuffs, ash and pumice.

Other alluvial deposits in Nazret area occur along the course of Mermersa stream and in the channels of other small ephemeral streams. In Mermersa stream, mainly sandy and sometimes silty and clayey channel fill deposits of thickness more than one meter were observed to occupy former troughs within the river bed. Deposition of sediments in fresh water is evidenced by the presence of gastropods and pellets in sections found along the course of Mermersa stream north-northwest of Nazret.

2.2.3. Structures and Volcanotectonic history

The main geological structures that have been observed in the study area include: faults, joints, and fractures (and other mesostructures like flow layering and folding associated with silicic lavas).

The area is intensively dissected by a number of minor and major normal faults running almost parallel to each other in a NNE-SSW direction and are usually arranged in "en echelon" fashion. These faults belong to the Wonji Fault Belt. They form steps and local graben-horst structures. Observed down throws estimated from the heights of the fault scarps range from few meters in the minor faults to more than 100 m (mainly west of Nazret). The faults dissect almost all units outcropping in the area and recent volcanism has been observed to be associated with these faults. Some faults are reported to be presently buried under the lacustrine sediments (Skutan et.al, 1982).

Indirect evidences of recent active faulting like very fresh fault scarps and traces of the fault movement have also been observed in few places.

Joints are abundant in the intensely welded ignimbrite unit (mainly in its middle portion) in the study area. The unit shows fracturing and network columnar jointing in the outcrops west of Nazret. Joints and fractures (mainly conchoidal) have also been observed in the other flows.

Flow layering and folding have mainly been observed in the basaltic and acidic lava flow units.

The volcanotectonic history of the study area can be summarized as follow.

The eruption of the fiamme ignimbrite and the aphanitic basalt units almost contemporaneously (the later being most probably emplaced first) occurred in the beginning. This event is believed to be followed by a major faulting event which mainly affected the western and southwestern parts of the area. The faulting resulted in the formation of structures like Kechema ridge. Following or together with the above faulting event occurred older acidic volcanism which gave rise to the flows that formed the Boku ridge. These volcanics were also highly affected by major faulting. Then comes the emplacement of the poorly welded lithic rich ignimbrite unit in the previously formed troughs and hence it presently occupies relatively lower topographic areas. Next occurred minor faulting event which formed small cliffs and step faults in the area. The fissure basalt eruptions which gave rise to the porphyritic vesicular basalts were related to these faulting. This was likely followed by the eruption of younger acidic volcanics which most probably occurred along previously formed faults. These acidic volcanics formed flow units and domes (Dibibisa and Migira domes). The formation of the precalderal volcanics, the formation of the calderal itself and the deposition of the post calderal volcanics at Gedemsa took place at this stage. The eruption of younger scoriaceous basalts and scorias (and associated flows) forming spatter and cinder cones occurred earlier and contemporaneously with the deposition of lacustrine, alluvial and colluvial sediments in the study area. The alluvial sediments represent the youngest deposition unit in the area; being present day deposits.

3. Hydrology

3.1. Precipitation

Precipitation can be defined as the amount of water that falls to the surface from the atmosphere as rain. It is one of the major parameters to be considered in dealing with the hydrogeology of an area.

Precipitation in the study area is recorded by rain-gauge. Two rainfall gauging stations are found in the study area and its surrounding. These stations are located at Nazret and at Wonji. The station at Nazret is class-3 recording only rainfall and temperature. While the Wonji station is class-1 and records rainfall, temperature, relative humidity, wind speed, radiation and evaporation. However, the precipitation record only from the station at Nazret is utilized in this study for the station is found at a more representative place, that is, almost at the centre of the area.

The mean annual precipitation depth recorded for the station at Nazret is 822.53 mm for almost 39 years period from 1952 to 1991 (Annex 1a). This value is taken to characterize every point in the entire study area or taken as a representative value owing to the small size of the area and minor topographic variation in it.

As can be seen from figure 3.1, there is a significant seasonal variation in the amount of rainfall. Almost more than 70% of the mean annual rainfall occurs in the four rainy months, from June to September with maximum monthly mean values reaching more than 200 mm. Some additional rain (20%) occur in the months of March, April and May. Very small amount occurs in the remaining dry season months with values of mean monthly rainfall reaching as low as 10 mm.

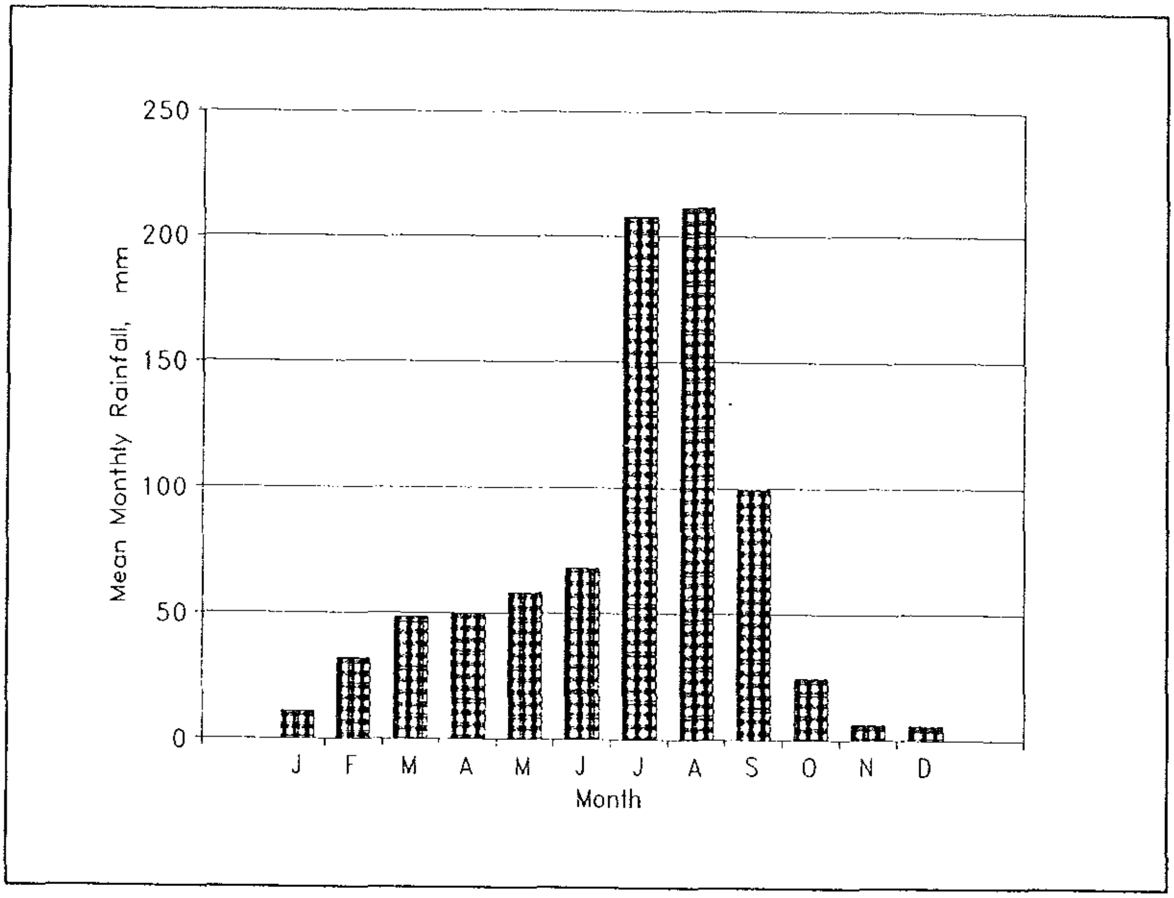


Fig. 3.1. Rainfall depth at Nazret (39 years).

The rainfall pattern for the record of the station at Nazret does not show significant variation, at least for the last 40 years, except in recent years the mean monthly values for the month of May showed a general increase (Figure 3.2). While no defined trend is shown by the annual total

Figure 3.3 shows that period of large rainfall coincides mostly with that of higher monthly mean temperature. This favours evapotranspiration in the study area. Of course, it is true that the amount of potential evapotranspiration exceeds the amount of precipitation for most part of the year in the area (Fig. 3.4).

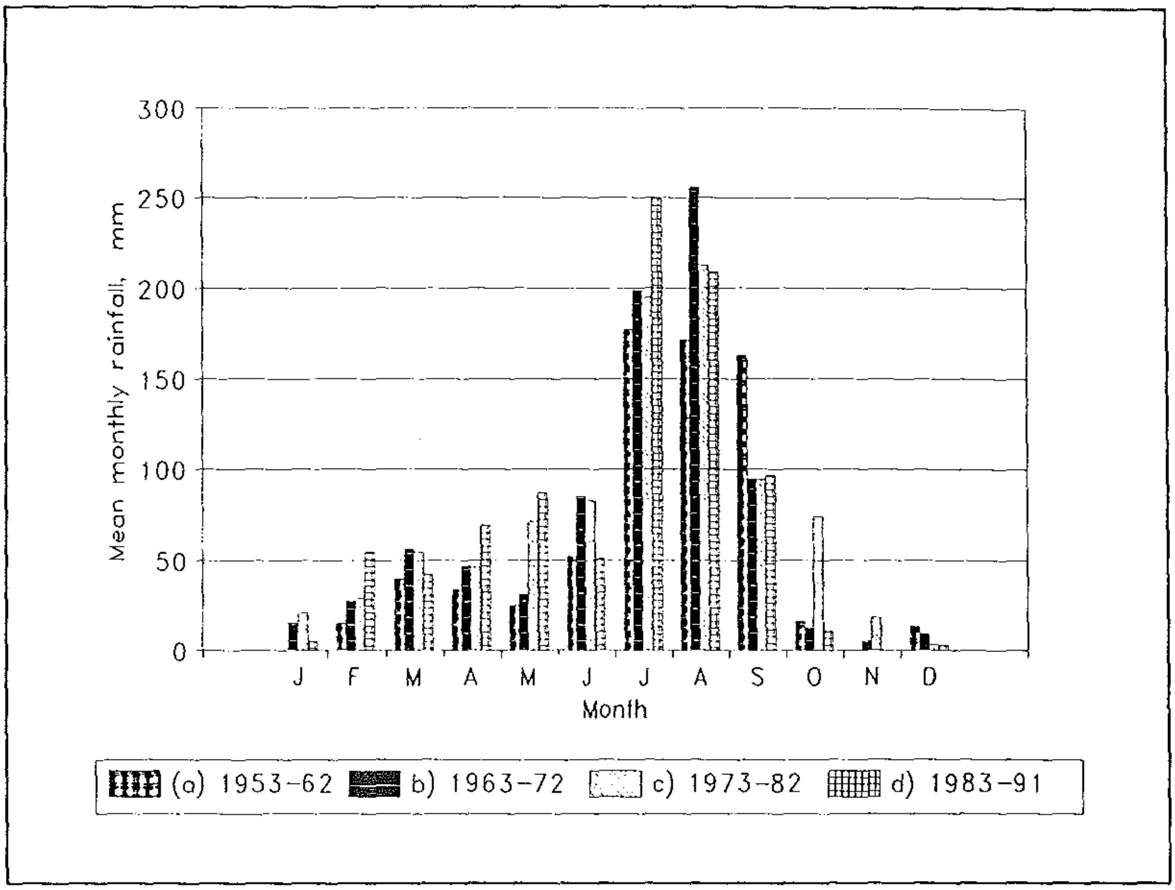


Fig. 3.2. Rainfall pattern (39 years).

Based on the Rainfall Coefficient (RC) (Table 3.1) which is the ratio between the mean annual rainfall and one twelfth of the annual mean (Daniel, 1974), three main periods can be identified in the study area. These are: a) a "big rain period" (with RC of more than 1) in the months of June , July, August and September with very high concentration of rainfall in July and August (RC of 3.0 and 3.1); b) a "small rain period" (RC between 0.6 and 0.9) in March, April and May; and c) a "dry period" in the rest of the year. The high concentration of rainfall in the above months together with other factors is the main cause of flush flooding problem that often occurs at Nazret.

Table. 3.1. Rainfall coefficient for Nazret.

Month	J	F	M	A	M	J	J	A	S	O	N	D
Rainfall	10.98	32	48.24	50.13	58.3	67.87	207.65	211.7	99.7	24.63	5.9	5.4
RC	0.2	0.5	0.7	0.7	0.9	1.0	3.0	3.1	1.5	0.4	0.1	0.1

Less than 0.6 - dry months

Greater than 0.6 - rainy months

0.6 - 0.9 small rains

1.0 - 1.9 big rains with moderate concentration

2.0 - 2.9 big rains with high concentration

> 3.0 big rains with very high concentration

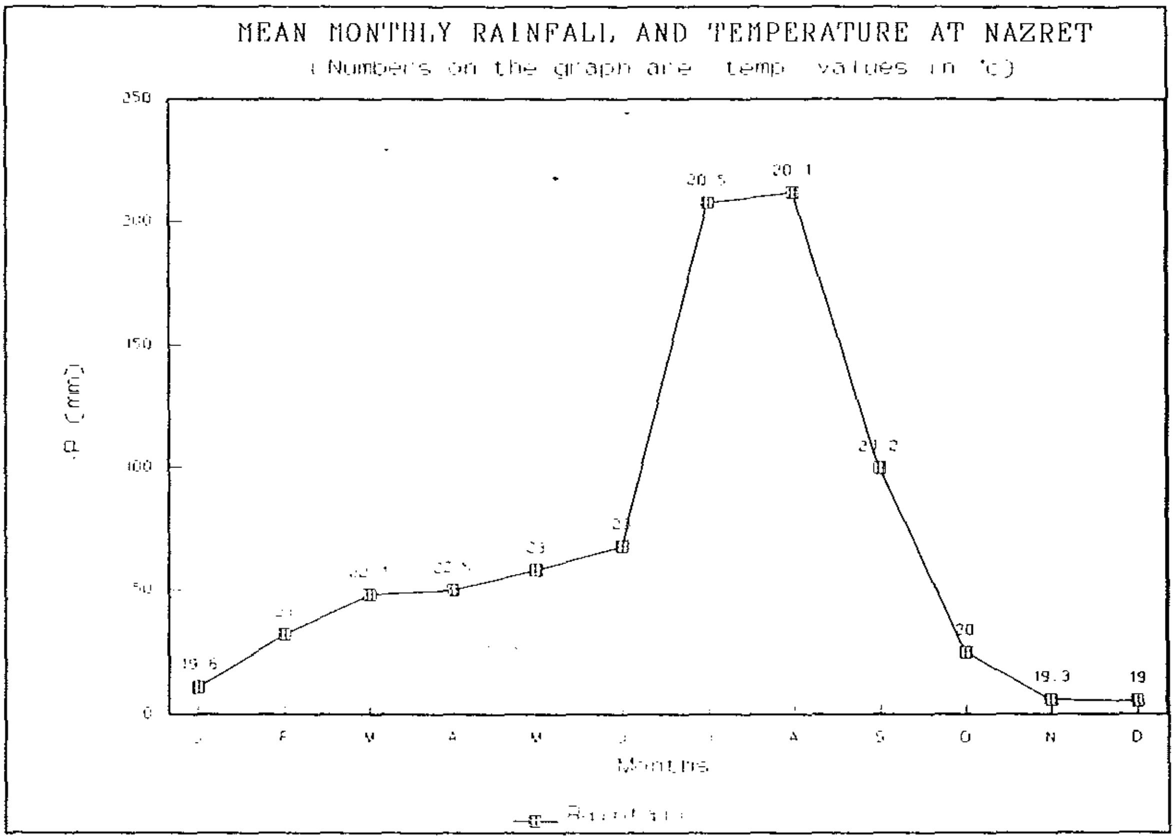


Figure. 3.3. Rainfall-Temperature Relationship at Nazret.

3.2. Evapotranspiration

One of the most important hydrologic parameter in considering water budget of an area is evapotranspiration. Evapotranspiration can be defined as the quantity of water that recycled to the atmosphere as vapour, either by direct evaporation from the soil and free water bodies, or by transpiration from vegetal cover. It is, therefore, a result of two phenomena; evaporation and transpiration. However, in field conditions it is not possible to separate the two processes. Instead their combined effect, i.e., evapotranspiration is usually considered.

Direct evapotranspiration measurement data have not been available for Nazret. However, Colorado pan evaporimeter measurements available for Wonji found 15 Km south of Nazret indicate an annual evaporation of 2390 mm (Table 3.2). Nevertheless, it is known that such instruments usually give higher values for such climate.

Table 3.2. Monthly evaporation at Wonji and Koka, in mm (Getahun Kebede, 1987).

Station	J	F	M	A	M	J	J	A	S	O	N	D
Wonji*	197	197	229.2	223.6	225.6	210.7	184.1	158.1	159.9	198.6	207.2	202.2
Koka**	205	194	190.2	193.8	186.6	166.6	164.5	138.4	128.1	187.6	199	195.8

Note: * record for the years 1969-1975

** record for the years 1970-1975

Various empirical and semi - empirical methods are presently employed for the estimation of evapotranspiration in an area. The most widely used methods utilize the concept of potential and actual evapotranspiration introduced by Thornthwaite. Potential evapotranspiration is defined as the amount of water that would be removed from the land surface by evaporation and transpiration process if sufficient water were available in the soil to meet the demand (Freeze and Cherry, 1979). The actual evapotranspiration represents the amount of evapotranspiration that occurs under field conditions (i.e, in determinate climatic conditions and with a given soil water content).

Other most common methods of calculating evapotranspiration include those of Blanly and Criddle (1950), Penman (1948), and Van Bavel (1966). However, from the available input data and from its minimal data requirement, the method employed by Thornthwaite is used for the computation of evapotranspiration in the study area.

The monthly values of evapotranspiration in an area can be estimated by using Thornthwaite empirical method which not only consider the monthly meteorological parameters (i.e, temperature and precipitation) but also takes into account the soil water characteristics and type of vegetation. The method uses air temperature as an index of the energy available for evapotranspiration (Leopold and Dune, 1978). The basic empirical formula for this method is expressed as :

$$E_T = 16\left(\frac{10T}{I}\right)^a \quad \text{in mm per month} \qquad 3.1$$

where E_T = monthly gross evapotranspiration (in mm)

T = mean monthly air temperature (in °C)

I = average annual heat index

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

The value of I is obtained by summing the monthly heat indices (i) computed from the mean monthly temperature of the consecutive months of the year by using the relation :

$$i = \left(\frac{T}{5}\right)^{1.5} \qquad 3.2$$

Then the yearly heat index will be the sum of the monthly values, that is,

$$I = \sum_{i=1}^{12} i \qquad 3.3$$

The gross potential evapotranspiration (commonly called the uncorrected potential evapotranspiration computed in equation 3.1 is for a standard month of 30 days each and 360 hours of daylight (i.e., 12 hours sunshine a day). This values must, therefore, be multiplied by the appropriate latitude factor that will account for the number of days per month and the length of day. The factor is expressed in the following equation (3.4) and the values for various latitudes are given in annex 2. Factor for 10°N latitude is considered for the study area.

$$K = \frac{N}{12} x \frac{d}{30} \qquad 3.4$$

where K = latitude factor (for monthly values)

N = maximum number of hours of solar energy/day

d = number of days in the month

Thus, the corrected monthly potential evapotranspiration (PE) is given as;

$$PE = K\ x\ UPE \qquad 3.5$$

where, UPE represents the uncorrected potential evapotranspiration values.

The procedure outlined by Leopold and Dune (1978) and Grassi (1992) for the computation of the actual evapotranspiration and the different hydrologic parameters related to it is applied here to estimate the evapotranspiration in the study area (Table 3.3).

The differences between precipitation and potential evapotranspiration are given in row 7 of table 3.3 This values define two seasons: a three month wet season when rainfall exceeded evapotranspiration and a 9 month dry season (indicated by negative values) when the demand is not met by precipitation for the respective months.

From field observation, it is known that the study area is mostly covered with a sandy soil with significant amounts of silt and clay. The available water holding capacity for such soils is approximately taken as 15% (150 mm of water per meter depth of soil) from annex 3 for fine sandy loam. The depth of root penetration for this soil type given in annex 3 is higher than what is actually observed in the field. Hence, an average rooting depth of 0.5 m is assumed for the vegetal cover in the study area.

The amount of water that will be retained by the soil for each dry season months (negative values of P-PE) can be found by using annex 4 for the corresponding potential water loss values with an available water capacity of 75 mm. Soil moisture values for the wet season months (July, August, and September) are obtained by adding the excess precipitation from row 7 (P-PE) to the soil moisture level at the end of the dry season. However, the soil moisture values can not exceed 125 mm because the soil could only hold this quantity of water. For this reason for July, August and September the moisture content remains at fixed capacity.

Negative values of change in the soil moisture (S) indicate the amount of contribution to evapotranspiration of the soil moisture storage.

To calculate the monthly values of actual evapotranspiration (AE), different hydrologic conditions must be taken into consideration. For the months in which the amount of precipitation exceeded the potential evapotranspiration (P-PE $\geq$ 0), actual evapotranspiration is equal to the potential evapotranspiration. This is true for the months of July, August and September in the study area. For the months in which the potential evapotranspiration is greater than the rainfall, the actual evapotranspiration is equal to the amount of precipitation plus the contribution from the soil moisture storage (i.e., AE = P + $\blacktriangle$SM).

The amount by which the actual and potential evapotranspiration differ in any amount is called the soil moisture deficit (Leopold and Dune, 1978). The monthly soil moisture deficit values are listed in row 12 of table 3.3.

The moisture (water) surplus which represents the amount of water contributing to infiltration and runoff is listed in line 13. For the months in which the difference between precipitation and potential evapotranspiration is less than or equal to zero (P-PE $\leq$ 0), it is assumed that there is no surplus, i.e., S = 0. But, in the case of months in which P - PE > 0, there are two possibilities: a) if the soil moisture storage of the preceding month is equal to the soil moisture storage of the month in question, (cf. August and September), then surplus is equal to the difference between precipitation and potential evapotranspiration; (b) if the soil moisture storage of the preceding month is ;less than (cf. July), there is a deficit, and then surplus is equal to precipitation (P) minus PE plus $\blacktriangle$SM.

In general, from Thornthwaite's method of calculation for the station at Nazret, assuming a uniform land cover of sandy loam soil, annual potential and actual evapotranspiration values of 978.15 mm and 615.90 mm respectively have been found. For the same station, of the total annual precipitation of 822.53 mm, the surplus which is available for infiltration and runoff has been computed to be 206.63 mm (Table 3.3). However, these values should not necessarily be taken as representative to every point in the entire study area because the input data is taken only for one station, a uniform land cover is assumed, and also for other hydrological reasons. For instance, within Nazret sub-catchment (Figure 3.5), the eastern part is believed to contribute more to evapotranspiration and infiltration than its western part for reasons that will be discussed later.

The results of Thornthwaite water balance calculation is also portrayed in figure 3.4..

Table 3.3 Thornthwaite water balance for Nazret (uniform land cover assumed)

	J	F	M	A	M	J	J	A	S	O	N	D	ANNUAL
T(C)	19.0	21.0	22.1	22.5	23.0	23.0	20.5	21.1	21.2	20.0	19.3	19.0	
i (I)	7.80	8.60	9.30	9.50	9.90	9.90	8.30	8.10	8.70	8.00	8.00	7.40	103.0
UPE (mm)	68.49	80.04	89.83	93.55	98.1	98.31	75.81	72.50	81.78	71.69	66.14	63.84	
K (10·N)	0.97	0.98	1.00	1.03	1.05	1.06	1.05	1.04	1.02	0.99	0.97	0.96	
PE (mm)	66.44	78.49	89.83	96.36	103.23	104.21	79.59	75.40	83.42	70.97	64.16	61.29	978.14
P (mm)	10.98	32.04	48.24	50.13	58.30	67.87	207.65	211.70	99.69	24.63	5.90	5.40	822.53
P-PE(mm)	-55.46	-46.40	-41.59	-46.30	-44.93	-36.34	128.06	136.3	16.27	-46.34	-58.26	-55.85	
APWL(mm)	-215.91	-262.31	-303.03	-355.03	-399.96	-436.30	-	-	-	-46.34	-104.60	-160.45	
SM (mm)*	4.00	2.10	1.00	1.00	1.00	1.00	75.0	75.0	75.0	38.0	20.0	8.0	
▲SM(mm)	-4.00	-1.90	-1.1	0	0	0	74.0	0	0	-37.0	-18.0	-12.0	
AE (mm)	14.98	33.94	49.34	50.13	58.30	63.87	79.59	75.40	83.42	61.63	23.90	17.40	615.9
D (mm)	51.46	41.50	41.49	46.23	44.93	36.34	0	0	0	9.34	37.26	45.34	
S (mm	0	0	0	0	0	0	54.06	136.30	16.27	0	0	0	206.63

* for 50 cm soil thickness.

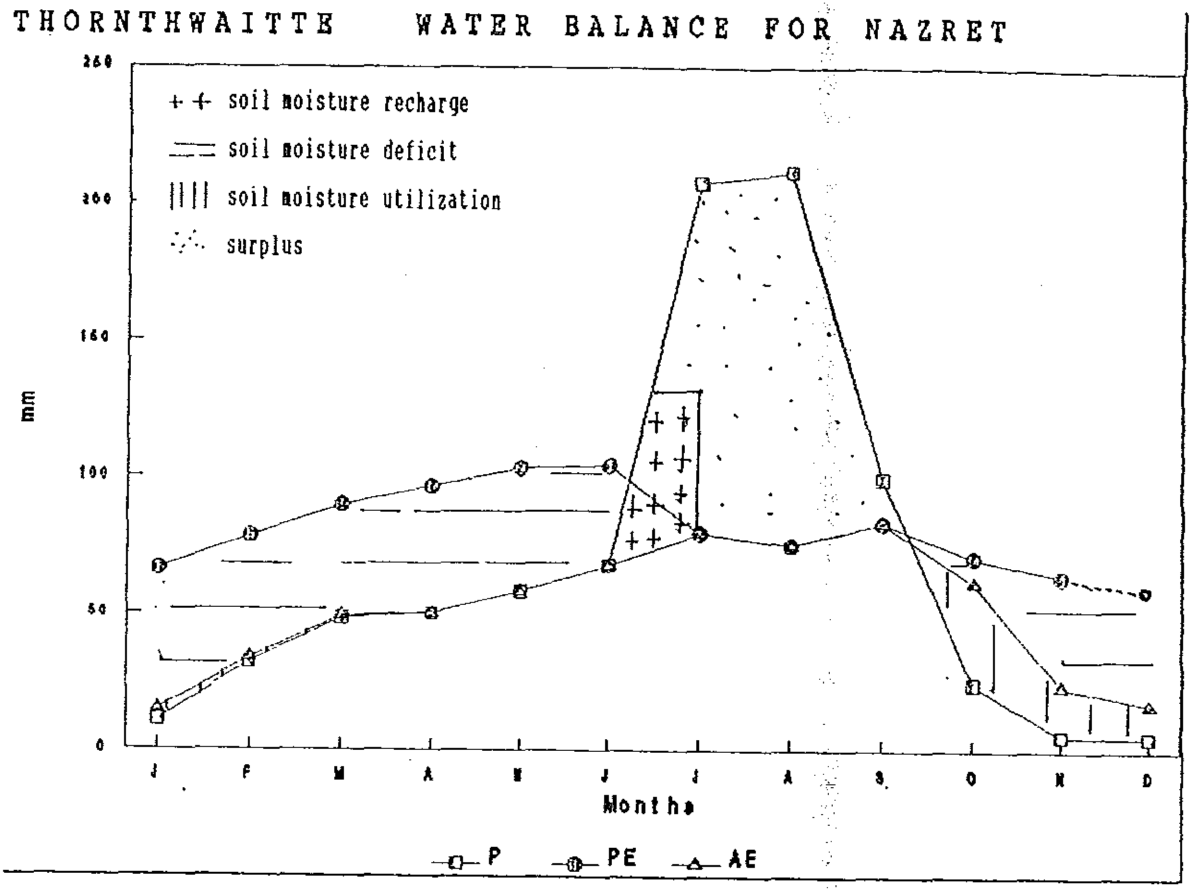


Fig. 3.4. Thornthwaite water balance.

3.3. Runoff

Runoff represents the amount of water that leaves a catchment as an outflow through surface channel (s). The runoff process is particularly affected by climate (including rainfall characteristics-intensity, duration, drop size), topography, soil characteristics (texture, structure, depth, initial moisture content, clay mineralogy), vegetation, and land use (Leopold and Dune, 1978).

Two general conditions can be identified as concerning to rainfall runoff relationship in an area. One is when high infiltration capacity that exceeded rainfall intensity exists and the other is when rainfall intensity exceeded the infiltration capacity of the soil. If rainfall intensity during a storm exceeded the infiltration capacity, water will first accumulate on the soil surface as depression storage and then will start to move downslope as overland flow (commonly called Hurton overland flow). This results in the production of storm runoff in the main channels. The amount of storm runoff in these channels will then rise to a sharp peak at the end of a storm and then tails off after a decrease in intensity occurred.

Runoff in the study area occurs only during rain events mainly at time of large storms. It is generally low or nil during small and short rains even in the rainy season depending up on the infiltration capacity of the lithologic units.

From the characteristics of the runoff, it is believed that rainfall events that generally exceed infiltration capacities of the soil are common in the study area particularly in the rainy season. That is, Hurton overland flow (Kirkbay, 1978) is the dominant producer of the storm runoff in the study area. However, the proportion of the rain events that are causing runoff is not known. But, one can safely say that the amount of runoff volume in the area is generally small and it is only contributed by intense rain events which are occurring mainly in the rainy season. The rate of intermittency of the streams and gullies increase with the different conditions from rainy to small rain and then dry periods of the year. The low drainage density in some parts of the area indicates a corresponding low runoff volume. The high evapotranspiration rate also contributes to the small amount of runoff.

As previously discussed, the study area includes a number of primary surface basins or sub-catchments. The water from these sub-catchments ultimately drain either into the Awash river through various water ways or into intermittent swamps both with in or outside the study area. All streams present within the study area are intermittent and the only perennial river in the vicinity is Awash about 9 Km south of Nazret.

Runoff that comes from the escarpments to the north enters the northern part of the study area and mainly flows into Mermersa stream which ultimately drains into an intermittent swamp found some 5 km to the northwest outside of the area.

In the eastern and northeastern parts of the area, runoff carried by a number of intermittent streams and gullies which start from the sides of the ridges and domes mainly disappears into the soil in the low-laying flat land within the area probably along a certain zone of weakness (buried fault or fracture). Some of these streams and gullies also form surface poundings.

The runoff from the western part of the area, carried by chiefly branched and parallel main streams, leaves the area and flows into the Awash river or into the Koka dam mainly during the rainy period.

To the south, runoff which mainly starts from the Boku ridge flows downslope towards Awash river and will either sink into the bordering alluvium or occasionally join the river only during large storms.

Nazret sub-catchment that occupies the central part of the study area and within which Nazret town is found(Figure 3.5) is characterized by a number of rills, gullies, and streams which mostly start from the sides of the ridges and domes surrounding the town. During rain events overland flow from the surrounding relatively high lands (mainly to the west, north west, and northeast of Nazret) runs to the rills and gullies forming a network of water ways that will drain increasingly into larger streams. Runoff mainly from the western portion of this sub-catchment leaves the area through a drainage channel that crosses the town and lastly joins the Awash river at times of large storms. On the other hand, water from the Eastern Part of the sub-catchment does not leave the area through surface water ways but remains within the area forming an intermittent swamp.

Therefore, the main portion of runoff that leaves the study area is from its northern, western and southern parts. To these can also be added the contribution from the Western Part of Nazret sub-catchment. Runoff from the eastern part of the study area and the eastern part of Nazret sub-catchment do not leave the area but either sinks to the ground or gives rise to temporary surface storage as swamps creating larger opportunity for infiltration and evaporation.

Quantification of total runoff leaving the entire study area was not possible owing to the absence of any sort of data on the flow of storm runoff through the streams and drainage ways in the area and also due to the large number of routes through which surface runoff is carried out of the area that could make flow measurements practically difficult.

From the values reported for neighbouring areas like Mojo (Tamiru, 1992) and from annex 5 (Sharma, 1983), a weighted runoff coefficient of 0.30 to 0.40 is assumed for the entire study area. Nevertheless, it should be noted that different portions of the area variably contribute to the runoff and hence are characterized by different runoff coefficients[5]. This is particularly dealt with in the computation of the water balance of Nazret sub-catchment in other section of this report.

Thornthwaite water balance calculation (Table 3.3) indicated that there would theoretically be no runoff (i.e., because there is no surplus available) except in the months of July, August and September in the area. In practice, however, storm flow can occur in any part of the year mainly depending on the intensity and duration of rains. That is, each intense rainfall is likely to produce storm runoff in the drainage channels. This might indicate some what limited use of the Thornthwaite method in areas with climatic conditions like that of Nazret.

3.4. Infiltration

One of the significant and also most difficult parameter to determine when studying hydrogeology of an area is infiltration or recharge to groundwater. From the Balance Equation it is known that the amount of infiltration is approximately equal to the amount of precipitation less the amounts contributed to runoff and evapotranspiration. So, it is obvious that factors favouring runoff and/or evapotranspiration in an area will indirectly cause a reduction in the amount of infiltration. In the study area, infiltration can occur through:

a) direct infiltration of water during rain events,

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[5] This is the concept of partial area contribution (Kirkbay, 1978; Freeze and Cherry, 1979).

b) seepage from surface runoff flowing through temporary stream channels which often have beds covered by permeable alluvium (mainly sand and gravel beds). Some of these intermittent streams happen to disappear in to the unconsolidated sediments as it can be observed in the eastern part of the area,

c) seepage through the major faults, fractures and joints that have incised many impervious rock units. They are important conduits for the ground water movement. Otherwise, recharge water might have taken much longer time to reach the deeply buried aquifers.

d) contribution through intermittent swamps, and

e) for the aquifers bordering Awash (southern part of the study area) a significant amount of recharge is contributed by the river.

However, contribution is expected to be large only in the last case (e). And, hence the study area as a whole is not expected to have high infiltration or recharge. This reduction of the overall infiltration is believed to be mainly due to:

a) many, but far from all, rainfall events which particularly occur in the main rain season are believed to be such that they cause what is called intensity runoff which is runoff that occurs when the rainfall is intensive for the infiltration process,

b) rainfall periods in the study area mostly coincide with periods of high temperature (Figure. 3.3) and this facilitates evapotranspiration,

c) unsorted nature of the sediments and other unconsolidated deposits (especially on the surface) which are mainly composed of mixtures of various sizes with the dominance of the finer components causing a significant decrease in the infiltration capacity. These materials cover significant proportion of the study area,

d) the presence of impervious bed rock cover mainly in the high elevated places (ridge, domes, etc.). These places are sloppy and almost barren of vegetation cover encouraging surface runoff during rain events,

e) the abundance of water ways in some parts of the area (rills, gullies, etc.), which usually start from the slopes, that will convey runoff rapidly to the main stream channels before it percolates to the ground, and to some extent

f) the presence of urban area (Nazret town) which have a sealing effect on the ground surface.

Except in the alluvial and other aquifers in the south which are bordering Awash river, it is believed that there is limited or no immediate groundwater response to the rainfall regime in many parts of the study area. Obviously, however, due to the importance of the faults, open joints and weathered zones as groundwater conduits some response could be expected in some parts of the area.

3.5. Water Balance

Water balance calculations are required to know the amount of water available for groundwater recharge in a given area of some known hydrologic parameters. As it is known from the Balance Equation, the amount of water available for groundwater recharge or infiltration (I) in an area is approximately equal to the amount of precipitation (P) less the amounts lost by evapotranspiration (E) and runoff (R), i.e.,

$$I = P - (E + R) \qquad 3.6$$

The study area, which is found within Awash River major basin, could not be identified with a single larger catchment area over which it is possible to conduct water balance study without an additional much more extensive investigation outside the area. This, of course, can not be done in a brief observation period. Hence, a small urban sub-catchment (primary basin) has been delineated and water balance study conducted over it.

Although the information available is inevitably incomplete so as to attain the desired degree of precision, it has been tried to conduct a water balance study over the delineated Nazret urban sub-catchment which occupied the central part of the study area (Fig. 3.5). This sub-catchment covers a surface area of about 71.06 Sq.Km. However, owing to the absence of runoff data in the sub-catchment and also to the brief observation period, it is not possible yet to give a quite explicit value to the amount of recharge and the calculations are expected to be less accurate than in cases where runoff data are available. It is believed that the results obtained from this calculation can be extrapolated over the entire study area to give an idea of the relative proportion of the different hydrologic parameters in general.

The estimation of the different hydrologic parameters is referred to herein the Nazret sub-catchment through water balancing that involves different important considerations and reasonable assumptions. Two very important assumptions are, therefore, considered in the water balance calculations. These are: a) subsurface inflow from the north into the sub-catchment (i.e, owing to groundwater flow mainly to the south direction) is assumed to be equalized by the subsurface outflow to the south from the sub-catchment; and b) the contribution of imported water from the wells outside the sub-catchment (Melka Hida well field mainly) is assumed to be compensated by the water withdrawal from the groundwater through the number of wells sunk at different localities within the sub-catchment.

Coming back to the estimation of the different hydrologic parameters; water balancing is done for the data of the years 1969-1975 because the pan evaporation measurement available for the station at Wonji, which is used in the estimation of evaporation loss, is recorded only for this period.

The mean annual precipitation depth in the sub-catchment for the above time interval is taken to be 881.56 mm as depicted in table 3.4 below.

Table 3.4. Mean Monthly Rainfall at Nazret (1969-75)

	J	F	M	A	M	J	J	A	S	O	N	D
1969	-	-	-	-	65.5	18.5	268.3	256.7	62.1	0.4	7.2	0.0
1970	51.1	27.9	81.1	28.4	18.4	11.5	155.7	305.7	112.1	4.4	0.0	0.0
1971	1.3	0.0	-	-	-	-	192.5	325.8	147.4	1.0	10.2	33.8
1972	1.3	10.5	96.2	86.3	28.0	130.0	273.2	249.8	85.7	6.5	0.0	0.0
1973	0.8	0.6	0.0	0.1	94.2	30.3	125.8	300.2	107.7	78.4	0.0	0.0
1974	0.6	7.3	100.2	0.0	77.3	118.5	180.8	161.7	171.0	1.5	0.0	0.0
1975	1.9	8.5	1.1	101.2	42.0	202.3	469.5	168.5	90.7	-	0.0	-
Mean	9.4	9.1	55.7	43.2	54.3	85.3	237.5	252.6	110.9	15.4	2.5	5.6

The amount of evapotranspiration (E) over the entire study area has been estimated in previous section using Thornthwaite method (Table 3.3 and Fig. 3.4), but only assuming a uniform land cover of sandy loam soil which is the dominant land type, without making any discrimination among the different land covers in the study area. This calculation gives an actual evapotranspiration value of 615.9 mm[6] in the area. However, this value should not be used in the detailed water balance calculation over the Nazret sub-catchment, which is characterized by different land cover types, for a better precision. Hence, evapotranspiration values are independently considered for each different land cover type within the sub-catchment area. This was done mainly using the Thornthwaite method for the data of the period 1969-75. The pan evaporation data from Wonji station for the same period is also used.

The other parameter in the water balance calculation is the amount of runoff that leaves the sub-catchment area. Some methods of estimating storm runoff like the SCS Method (Stephenson, 1980; Nutreja, 1986) are developed for individual storms. Other methods like the Rational Method (Leopold and Dune, 1978; Nutreja, 1986; Garg, 1989) require storm intensity and duration data which are not available for the study area. On the other hand it should be worth mentioning that the water balance calculation depicted in table 3.3 indicates that there would theoretically be no runoff (because there is no surplus available) except in the months of July, August and September in the area. This is also true for the calculations shown in tables 3.5a and 3.5b. In practice, however, storm runoff can occur at any time of the year depending on the intensity and duration of rains. Of course, runoff is generally low or nil during small and short rain events even in the rainy seasons. Therefore, runoff values derived from these calculations will

[6] This value was calculated for 39 years (1952-1991) data.

not be used in the forth coming detailed water balancing which involves consideration of the different landuse types.

As mentioned earlier, there are no flow measurement data for out-going runoff leaving Nazret sub-catchment through the outlet that carries water to the Awash River at time of storms. However, from the values of runoff coefficients determined for similar catchments in neighbouring areas (like Modjo basin; Tamiru, 1992) and from annex 5 (Sharma, 1983 and Garg, 1989), different runoff coefficient values have been assigned over the various land cover types identified within the sub-catchment (Table 3.6).

Table 3.6. Runoff coefficient over the different land-cover types in the Nazret sub-catchment.

Land-cover type	MCSC	MIRC	BA		MUSC
			50%	50%	
Runoff coefficient	0.30	0.90	0.95	0.35	0.35

MCSC: Mostly cultivated soil cover or cropland
MIRC: Bare rock or mostly impervious rock cover
BA : Built-up area or urbanized zone
MUSC: Bare ground or mostly uncultivated soil cover

Lastly, from the Balance equation, the amount of infiltration over each land cover type and on this basis over the whole Nazret sub-catchment has been determined.

Detailed treatment of the water balance, in terms of computing the total volume of water which is available to meet field capacity of the soil and for groundwater recharge, involves not only consideration of various land cover types but also different hydrologic conditions over the different parts of the sub-catchment. In light of this, the sub-catchment area was divided into two nearly equal parts which themselves are characterized by different land-cover types, based on their contribution to the outgoing runoff. These are: a) Western Part of Nazret sub-catchment with an area of 37.31 sq.km, i.e., about 52.2% of the total 71.06 sq.km; and b) Eastern Part of Nazret sub-catchment with an area of 33.75 sq.km, i.e., 47.5%. Runoff from the Western Part leaves the area through the outflow channel. In this part, each intense rainfall with sufficient duration is likely to cause outgoing runoff. While runoff from the Eastern Part does not leave the area through surface water ways thereby contributing generally very small or nil to the total outgoing runoff from the sub-catchment as a whole. Water from this part will ultimately evapotranspire or infiltrate. Accordingly, therefore, further consideration of the water balance was taken separately over each part and hence the computation is split into two.

Generally, five different main land cover types were broadly identified within the Nazret sub-catchment wherein different hydrologic response , with respect to the four hydrologic parameters in the balance equation (P,E,R and I), could be recognized. That is to say, the relative importance of each hydrologic parameter over the various portions (land covers) of the sub-catchment is believed to be significantly different. Thus, the different land cover types were taken to be generally characterized as discussed below.

a) Mostly cultivated soil cover or cropland (MCSC): this land type is relatively spatially widespread and occupies low-lying flat lands. It is largely cultivated and very limited or negligible proportion of it is fallow. Higher vegetation cover (acacia, etc.) is very scarce. A sandy loam soil which is the commonest type in the area is taken to characterize this land type as also is considered in the Thornthwaite water balance calculation in a previous section. Here heterogeneity that may occur in the soil from place to place is ignored for simplicity. Evapotranspiration computed through Thornthwaite method of calculation (Table 3.5a) for this land-cover is estimated to be 589.72 mm.

Overland flow in the MCSC land type will only occur during large intense storms and a runoff coefficient of 0.30 is assigned to it (Table 3.6).

Table 3.5a. Water balance over MCSC land type in the Nazret sub-catchment.

	J	F	M	A	M	J	J	A	S	O	N	D	Annual
T (°C)	19.5	20.8	22.1	23.2	23.5	23.3	20.4	20.2	20.8	20.1	18.5	18.2	
i (I)	7.7	8.5	9.3	10.0	10.2	10.0	8.2	8.1	8.5	8.1	7.1	6.9	102.6
UPE (mm)	67.86	78.46	89.93	100.32	103.26	101.29	75.11	73.46	78.46	72.65	60.28	58.10	
K (10°N)	0.97	0.98	1.00	1.03	1.05	1.06	1.05	1.04	1.02	0.99	0.97	0.96	
PE (mm)	65.82	76.89	89.93	103.33	108.42	107.37	78.86	76.40	80.03	71.92	58.47	55.77	
P (mm)	9.36	9.13	55.72	43.20	54.25	85.3	237.54	252.63	110.96	15.36	2.48	5.63	881.56
P-PE(mm)	-56.46	-67.76	-34.21	-60.13	-54.17	-22.07	158.68	176.23	30.93	-56.56	-55.99	-50.14	
APWL(mm)	-219.15	-286.91	-321.12	-381.25	-435.4	-457.49	-	-	-	-56.56	-112.55	-162.69	
SM (mm)*	4.1	1.3	1.0	1.0	1.0	1.0	75.0	75.0	75.0	42.0	18.0	9.5	
ΔSM (mm)	-5.4	-2.8	-0.3	0	0	0	74	0.0	0.0	-33.0	-24.0	-8.5	
AE (mm)	14.76	11.93	56.02	13.20	54.25	85.30	78.86	76.40	80.03	48.36	26.48	14.13	589.72
D (mm)	52.06	64.96	33.91	60.13	54.17	22.07	0	0	0	23.26	33.99	41.64	
S (mm)	0	0	0	0	0	0	84.68	176.23	30.93	0	0	0	291.84

* for 50 cm soil thickness

b) Bare rock or Mostly impervious bed rock cover (MIRC): this land type is taken to represent those places covered by largely impervious bed rocks which are usually elevated areas, ridges and domes. Here, it should be noted that there are tectonized (fractured and jointed) and weathered zones in some places, within this land type, wherein possible deep percolation to the groundwater may sometimes be very important. However, those zones are generally considered to be of negligible aerial extent. The MIRC land type is some times characterized by sparse vegetation which are mainly bushes and shrubs. In the Western Part of Nazret sub-catchment the MIRC is represented by mainly Kechema Ridge and other scanty places to the north. While in the Eastern Part it is given by mainly Boku Ridge and by the rhyolitic domes.

Very small or insignificant amount of evapotranspiration is expected to occur over the MIRC land type. Since they chiefly represent sloppy places (ridges and scarps), rain water that falls over these places will be rapidly channelled downslope to gullies and streams before getting enough time for evapotranspiration to occur. Almost all rain storms over this land cover are believed to produce Hurton overland flow and a runoff coefficient of 0.90 is assigned (Table 3.6).

Table 3.5b. Water balance over MUSC land type in the Nazret sub-catchment.

	J	F	M	A	M	J	J	A	S	O	N	D	Annual
T (°C)	19.5	20.8	22.1	23.2	23.5	23.3	20.4	20.2	20.8	20.1	18.5	18.2	
i (I)	7.7	8.5	9.3	10.0	10.2	10.0	8.2	8.1	8.5	8.1	7.1	6.9	102.6
UPE (mm)	67.86	78.46	89.93	100.32	103.26	101.29	75.11	73.46	78.46	72.65	60.28	58.10	
K (10°N)	0.97	0.98	1.00	1.03	1.05	1.06	1.05	1.04	1.02	0.99	0.97	0.96	
PE (mm)	65.82	76.89	89.93	103.33	108.42	107.37	78.86	76.40	80.03	71.92	58.47	55.77	
P (mm)	9.36	9.13	55.72	43.20	54.25	85.3	237.54	252.63	110.96	15.36	2.48	5.63	881.56
P-PE(mm)	-56.46	-67.76	-34.21	-60.13	-54.17	-22.07	158.68	176.23	30.93	-56.56	-55.99	-50.14	
APWL(mm)	-219.15	-286.91	-321.12	-381.25	-435.4	-457.49	-	-	-	-56.56	-112.55	-162.69	
SM (mm)**	1.0	1.0	1.0	1.0	1.0	1.0	25.0	25.0	25.0	2.0	1.0	1.0	
▲SM (mm)	0	0	0	0	0	0	24.0	0	0	-23.0	-1	0	
AE (mm)	9.36	9.13	55.72	43.3	54.25	85.3	78.86	76.40	80.03	38.36	3.48	5.63	539.72
D (mm)	52.06	54.96	33.91	60.13	54.17	22.07	0	0	0	23.56	33.99	41.64	
S (mm)	0	0	0	0	0	0	134.68	176.23	30.93	0	0	0	341.84

** for 25 cm soil thickness

c) Bare ground or Mostly uncultivated soil cover (MUSC): this land type is considered to represent mostly thin (usually not more than 0.25 m) soil covered portions which are not cultivated. It mainly occupies relatively flat lands and also slopes in few instances.

Evapotranspiration over the MUSC land type, estimated through Thornthwaite's method, is 539.72 mm as depicted in table 3.5b.

Even though, still only large intense storms are likely to produce overland flow in this land type, it a bit largely favours runoff than do the MCSC land type. A runoff coefficient of 0.35 is therefore assigned to this portion of the sub-catchment (Table 3.6).

d) Built-up area or Urbanized area (BA): this land type represents the urbanized part of the watershed which is given by the town of Nazret.

The pavements, roofs, asphalt roads, etc., which are taken to represent sealed grounds are considered totally impervious and almost all rain storms are believed to produce overland flow. This portion of the built-up area is taken to cover 50% of the urbanized zone (Leopold and Dune, 1978). Evapotranspiration from the impervious portion of the built-up area is believed to be negligible and a runoff coefficient of 0.95 is assigned to it.

The remaining 50% of the urbanized zone which represents play grounds, house yards, etc. is recognized as a bare ground or mostly uncultivated land cover type (MUSC) which was discussed above.

e) Intermittent swamp (ISP): this land-cover type represents a temporary surface pounding places. It is mainly found southeast of Nazret. Other places with limited aerial extent are found just southwest and northwest of the town.

In the Eastern Part of Nazret sub-catchment, overland flow from the surrounding slopes drain in to the low-lying flat areas forming a swamp mainly in the rainy season. This swamp is partly found within the municipal boundary of the town.

Evaporation from very thin free water surface is considered here. The pan evaporation values from a station at Wonji with a pan coefficient of 0.7 is taken in the water balance calculation over this land cover type.

Table 3.7 shows the aerial extent and relative proportion of each of the above mentioned land cover types with in the Western and Eastern parts of the Nazert sub-catchment. It is believed that those are the major land cover types that could be recognized and other types that might be identified occupy only very limited proportion of land and, hence, are having negligible significance in the water balance calculation.

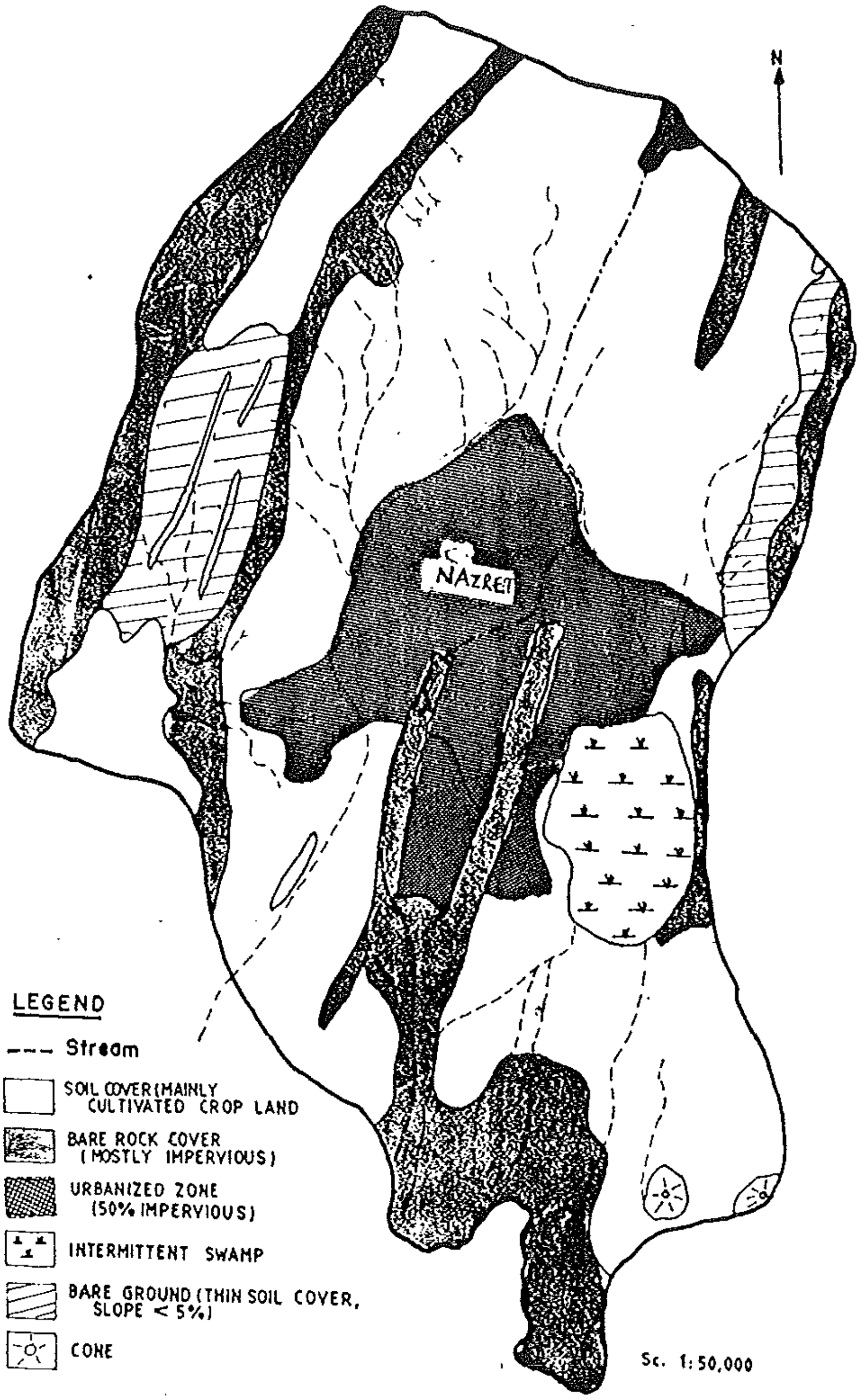

FIG.3.5 Nazret Sub-Catchment, Land Use

Table 3.7. Land cover types in the Nazret sub-catchment and their aerial coverage.

Land cover type	Aerial Coverage (Sq.Km)		
	Western part	Eastern part	Total
MCSC	21.01	20.28	41.29
MIRC	7.60	6.00	13.60
MUSC	3.50	1.17	4.67
BA	5.20	4.00	9.20
ISP	Negligible	2.30	2.30
Total	37.31	33.75	71.06

The water balance calculation is split in to two over a) Western and b) Eastern Parts of the sub-catchment as follows:

a) Water balance over the Western Part of Nazret sub-catchment:

Precipitation:

The annual precipitation depth taken in this calculations is 881.56 mm which is considered as a representative value over the area for the given period, i.e.,1969-75. In terms of water volume measured in m^3, this is equivalent to $P_W = (0.88156)$ m x $(37.31) \times 10^6$ m^2 = 32.39×10^6 m^3 over the western part of Nazret sub-catchment.

Evapotranspiration:

Here, different cases among the various land cover types should be considered. Hence,

- for the land cover type MCSC; an evapotranspiration depth of 589.72 mm (obtained from table 3.5a) is taken. This is equivalent to (0.58972) m x (21.01) x 10^6 m^2 = 12.39 x 10^6 m^3 over the area of this land cover.

- for the MUSC; an evapotranspiration depth of 539.72 mm (obtained from table 3.5b) which is equivalent to 1.89 x10^6 m^3 over an area of 3.5 sq.km.

- for the land cover type BA (enclosed within the western part of the sub-catchment) two cases are identified. That is, a) 50 % of the area is taken to be totally impervious and evapotranspiration from this part is assumed negligible because rain that falls over this portion is believed to drain soon to the drainage ways before getting enough time for evapotranspiration to occur; and b) the remaining 50% of the BA is taken to be of the land type MUSC with an evapotranspiration depth of 539.72 mm (obtained from Table 3.5b). This value is equivalent to (0.53972) m x (2.6) x 10^6 m^2 = 1.40 x 10^6 m^3 over this portion of the built-up area.

- for the land cover type MIRC the evapotranspiration is assumed to be negligible.

Therefore, the total volume of evapotranspiration from the Western Part of the sub-catchment is given to be (E_W) = 12.39 x 10^6 m^3 + 1.40 x 10^6 m^3 + 1.89 x 10^6 m^3 = 15.68 x 10^6 m^3. This value accounts for about 47.67% of the annual precipitation over this part.

Runoff:

Different runoff coefficients, according to table 3.6, are assigned to the different land cover types. Hence,

- for the land cover type MCSC, a runoff coefficient of 0.30 is taken. This gives an equivalent volume of runoff which is equal to (0.30) x (0.88156) m x (21.01) x 10^6 m^2 = 5.56 x 10^6 m^3;

- for the land cover type MIRC, a runoff coefficient of 0.90 is taken. This gives an equivalent volume of runoff of (0.90) x (0.88156) m x (7.6) x 10^6 m^2 = 6.03 x 10^6 m^3;

- for the land cover type BA, a) 50% impervious, a runoff coefficient of 0.95 is equivalent to a runoff volume of about (0.95) x (0.88156) m x (2.6) x 10^6 m^2 = 2.18 x 10^6 m^3; and b) for the remaining 50% which is taken to be the land type MUSC with a runoff coefficient of 0.35 the volume of runoff was estimated to be (0.35) x (0.88156) m x (2.6) x 10^6 m^2 = 0.80 x 10^6 m^3;

- for the part of the area occupied by the MUSC type, with a runoff coefficient of 0.35, the runoff volume is calculated to be (0.35) x (0.88156) m x (3.5) x 10^6 m^2 = 1.08 x 10^6 m^3.

Hence, the volume of water that could be available to leave the Western Part of Nazret sub-catchment as surface runoff is estimated to be 15.65 x 10^6 m^3. However, this whole amount will not possibly leave the area for there would practically be infiltration along the stream channels and also a portion of this water might sink to the soil along fractured zones mainly in the low lying flat lands. The later case is taken to be negligible in this part of the sub-catchment. The losses along the stream channels are very difficult to quantify. Some authors (Lensley and references therein, 1980) give percolation rates averaging 0.667 m water per day during floods in a typical desert wash which is usually sandy covered and highly permeable. Other authors (White, 1930) observed losses as great as 2.8% of the flow per kilometre. In light of these, and taking in to consideration the chiefly sandy stream beds, the total length of the main channels which is about 25 km, and the type of runoff which is by large storm flow in this part of the sub-catchment the losses along the stream channels were roughly estimated to be about 20% of the total available water for surface flow or runoff. This gives a total volume of losses through the stream channels of 3.13×10^6 m^3.

Therefore, the total volume of water that actually leaves the Western Part of Nazret sub-catchment as surface runoff is estimated to be $R_W = 12.50 \times 10^6$ m^3. This accounts for about 38.01% of the precipitation over this part of the area. This value do also represent the total runoff (R) leaving out from the entire Nazret sub-catchment for the contribution to the outgoing runoff of its eastern part is negligible or nil.

Infiltration:

From the Balance Equation, therefore, the amount of water available for infiltration or recharge in the Western Part of Nazret sub-catchment is estimated: $I_W = P_W - (E_W + R_W)$;

$I_W = (32.89) \times 10^6$ $m^3 - (15.68 + 12.50) \times 10^6$ $m^3 = 4.71 \times 10^6$ m^3. This value accounts for about only 14.32% by volume of the amount of mean annual precipitation over the Western Part (see table 3.8).

b) Water balance over the Eastern Part of Nazret sub-catchment:

A slightly different approach is used to calculate the water balance in the Eastern Part of the sub-catchment (with an area of 33.75 sq km) which is characterized by negligible or no contribution to the total outgoing runoff from the whole sub-catchment and also by the presence of an intermittent swamp.

Precipitation:

Same precipitation depth (i.e.,881.56 mm) as in the above case is considered here also. In terms of water volume, however, this is equivalent to $P_E = 29.75 \times 10^6$ m^3 over an area of 33.75 sq.km.

Evapotranspiration:

An evapotranspiration depth of 589.72 mm (Table. 3.5a) is considered over the MCSC land cover type. Hence, a water volume of (0.58972) m x (20.28) x 10^6 m^2 = 11.96 x 10^6 m^3. For the MUCS land type with an area of 1.17 sq.km in this part of the sub-catchment, the volume of evapotranspiration is assumed to be (0.53972) m x (1.17) x 10^6 m^2 = 0.63 x 10^6 m^3.

For the MIRC land type and for the impervious portion of the built-up area (50 %) enclosed within this part of the sub-catchment, the evapotranspiration is assumed negligible for reason previously mentioned. For the remaining 50 % of the built-up area (i.e., 2 sq.km) same evapotranspiration rate as the MUSC land type (i.e., 539.72 mm) is taken giving an equivalent volume of 1.08 x 10^6 m^3.

Another contribution to the evapotranspiration comes from direct evaporation of water from the intermittent swamp with an area of about 2.3 sq.km. This surface pounding occur only for certain time of the year, mainly in the three rainy months of July, August and September. Pan evaporation values of 184.1 mm, 158.2 mm, and 159.9 mm (Table 3.2), respectively for the three months, recorded at Wonji is used to estimate the evaporation loss from this thin free water reservoir with pan coefficient of 0.7. The actual evaporation rate in these three months is given to be (502.2) mm x (0.7) = 351.54 mm. The water loss in terms of volume from the swamp is, therefore, estimated to be

(0.35154) m x (2.30) x 10^6 m^2 = 0.81 x 10^6 m^3. For the rest of the year this place is dehydrated and hence a normal evapotranspiration rate over the land type MUSC is assumed. Thus, for the nine months from October to June, with monthly evapotranspiration values depicted in table 3.5b, the evapotranspiration loss is about (0.30443) m x (2.3) x 10^6 m^2 = 0.70 x 10^6 m^3. Therefore, the total amount of evapotranspiration over the Eastern Part of the sub-catchment is estimated to be (E_E) = (11.96) x 10^6 m^3 + (1.08) x 10^6 m^3 + (0.81) x 10^6 m^3 + (0.70) x 10^6 m^3 + (0.63) x 10^6 m^3 = 15.18 x 10^6 m^3. This value represents about 51.03% of the annual precipitation over this part of the area.

Runoff:

No or negligible amount of water leaves this part of the sub-catchment as surface runoff. Overland flow from the surrounding slopes will ultimately drain into the low-lying flat land resulting in surface pounding of water or swamp mainly during rainy season. The contribution to overland flow of the different land covers, in fact, varies significantly. However, this portion of the precipitation will remain within the area. Therefore, the hydrologic parameter R, (i.e., Runoff) in the Balance Equation will be taken to be approximately zero for the Eastern Part of Nazret sub-catchment.

Infiltration:

Besides the amount lost through evaporation from the swamp, all the volume of water that could have left this part of the sub-catchment as surface runoff contributes to infiltration. Therefore, the total amount of water that is available for infiltration or recharge in the Eastern Part of the sub-catchment as a whole is the sum of the original amount of available water for infiltration over each land cover type and the contribution from the amount that would have left the area as runoff if there was an outlet. The available water for runoff that remains within the area will, as previously said, contribute to mainly infiltration and to some extent to evapotranspiration. The contribution to the later is mainly through direct evaporation from the swamp and this has been taken care of in the calculation above. Thus, the total actual amount of water available for infiltration in this part can be estimated from the Balance Equation by taking the runoff component, R, equals to nil. That is, $I_E = P_E - E_E$. This gives an amount of available water for recharge of about $I_E = (29.75) \times 10^6$ m^3 less $(15.18) \times 10^6$ m^3 = 14.57×10^6 m^3. This value accounts for about 48.97% of the annual volume of precipitation over this part of the sub-catchment which is quite a large amount especially when compared to that of the western part with infiltration only of about 14.32% of the annual volume of rainfall.

Table 3.8 summarizes the water balancing and amount in terms of volume (m^3) of the various hydrologic parameters over the two parts of Nazret sub-catchment as well as over the entire sub-catchment as a whole on the basis of the above discussion and calculation. Accordingly, the amounts over the whole sub-catchment are estimated to be :

Precipitation (P_T) = 62.64×10^6 m^3

Evapotranspiration (E_T) = 30.86×10^6 m^3

Runoff (R_T) $= 12.50 \times 10^6\ m^3$

Infiltration[7] (I_T) $= 19.29 \times 10^6\ m^3$

Table. 3.8. Water balance over Nazret sub-catchment.

Hydrologic Parameters	Amount in terms of volume in m^3 (10^6)			Amount in percentage P_T over the entire sub-catchment
	Western Part	Eastern Part	Whole sub-catchment	
P	32.39	29.75	62.64	-
E	15.68	15.18	30.86	49%
R	12.50	0.00	12.50	20%
I	4.71	12.50	19.29	31%

Generally speaking one can say that about 20% of the annual rainfall is transported out of Nazret sub-catchment as surface runoff. From the remaining 80%, about 49% is lost through direct evapotranspiration. And the rest, about 30%, is accounted for infiltration representing both the amount of water available to meet the field capacity of the soil and the amount that joins the groundwater. However, a significant variation in the relation among these parameters occurs over various portions of the sub-catchment and also in different seasons (owing to the seasonal variation of mainly rainfall).

On the whole, the Eastern Part of the sub-catchment very much favours infiltration (49% of P) than the Western Part in which infiltration to the ground from rainfall is expected to be limited (14% of P). Even in the Eastern Part where there is relatively significant amount of available water for

[7]This value represents the amount of water available to meet the field capacity of the soil and groundwater recharge. It is not the same as the "surplus" in Thornthwaite water balance calculation which is the amount that remains after evapotranspiration (E) and field capacity of the soil are taken care of.

infiltration, no immediate response of the groundwater level to the rainfall regime is expected owing to the large depth to the groundwater and to the type of soil/sediment cover. On the other hand, surface out-flow from Nazret sub-catchment is almost entirely contributed by its Western Part. Losses by evapotranspiration are almost equal over the Western and Eastern parts except in the later case it is slightly higher due to the presence and hence direct evaporation from the intermittent swamp.

4. Hydrogeology

4.1. General

The major controlling factor to the nature and distribution of aquifers in a geologic system are lithology, stratigraphy, and structure of the lithologic units and formations (Freeze and Cherry, 1979). In nonindurated deposits the lithology and stratigraphy constitute the most important controls. While the structure control is more important in the case of dense and indurated deposits.

Different lithologic units that are recognized in the study area are characterized by different hydrologic properties. This differences are also sometimes observed even with in the same unit. The main aquifers in the area are alluvial and lacustrine sediments, pyroclastic rocks, and weathered and fractured volcanic rocks.

In broad senses the aquifers found in the area can be subdivided into two main categories; these are:

a) nonindurated sediments and fragmental or brecciated volcanic deposits.These aquifers have their permeabilities mainly attributable to the primary porosities; and

b) dense or massive volcanic rocks which are characterized by permeabilities associated to fractures, joints, faults, zones affected by weathering, and/or interbeds.

The nonindurated alluvial and lacustrine sediments in the area are composed of gravel, sand, silt, or clay size particles that are not hardened by mineral cementing. Those zones with the coarse sediments like sand and gravel form very important aquifers. While the clays, silts, or the loam are poor aquifers and form typical aquitards in different places in the area.

The fragmental or brecciated volcanic deposits mainly constitute various pyroclastic rocks which include brecciated basalts (scoria, cinder and spatter products), pumice falls, poorly welded or unwelded tuffs, ashes and volcanic sand[8]. These deposits usually form very porous and permeable zones representing important aquifers in many places in the area. However, some of these deposits like the volcanic ashes and unwelded tuffs (when composed of different sized particles) are characterized by may be high porosities but with low permeabilities.

Fractured, jointed, faulted and/or weathered zones mainly in the basalts and ignimbrites sometimes form important aquifers in the study area. The faults and fractures also serve as important conduits for groundwater movement and recharge. When dense and unfractured, however, these volcanic rocks are typical aquicludes.

It has been tried to classify the aquifers of the area and map the different lithologies according to their permeabilities in a scale 1:25,000. This was done based mainly on field observations supported by some quantitative considerations that involved calculations of specific capacity, transmissivity and permeability of aquifers from single-well constant rate pumping test data available only for some of the wells in the area.

Therefore, the rocks of the area were broadly classified into five aquifer classes or permeability groups, that is, rocks with Very low, Low, Moderate, Good or Very good

[8] The volcanic sand could be either pyroclastic or detrital in origin.

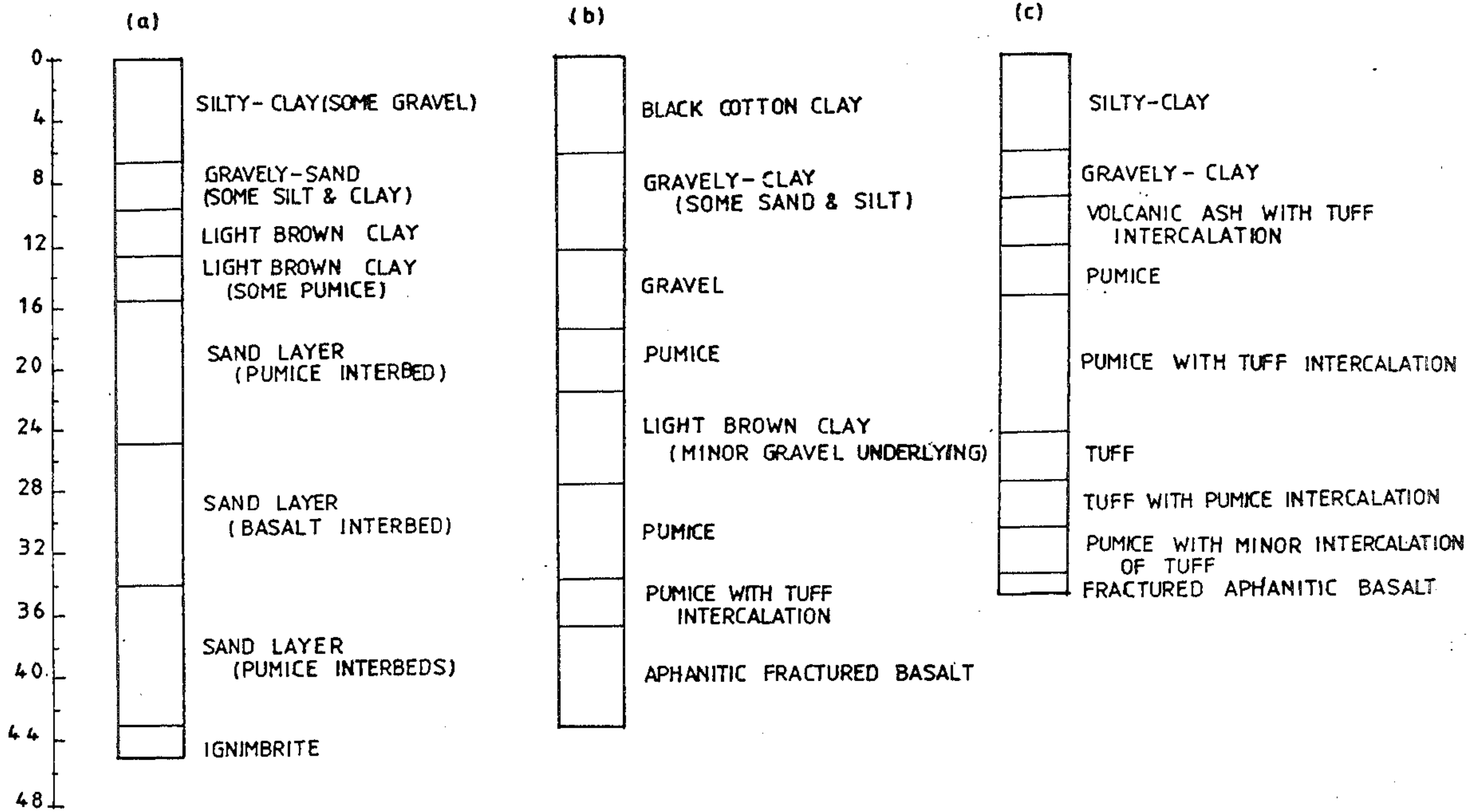

Fig.4-1 Lithiological Log of Well No (a) 10, (b) 12 & (c) 13 at Melka Hida, Nazret.
(Source: Menhasebo and Yirga. 1989Sc. 1:400)

permeabilities. Hence, on the hydrogeologic map the various lithologies are put as follow:

a) Very low permeability group: rhyolitic flows and domes, intensely welded unfractured ignimbrites and fresh unfractured aphanitic basalt,

b) Low permeability group: unwelded tuffs (mainly composed of ash), lithic rich ignimbrites, fresh unfractured and/or unweathered vesicular basalts, diatomite, fine grained sediments

c) moderate permeability group: ash flows and falls, moderately fractured vesicular and aphanitic basalts, weathered and/or jointed ignimbrites,

d) high permeability group: weathered vesicular basalts, weathered aphanitic basalts, alluvials, and

e) Very high permeability group: coarse grained lacustrine sediments, volcanic sand, scorias and cinders, pumice falls, highly fractured (jointed) vesicular basalts.

The hydrogeologic property of the different lithologies occurring in the area is described in different sections below.

4.2 Aquifer Characteristics of the Different rock Units

4.2.1. Alluvial and Lacustrine Sediments

Wells tapping alluvial and other aquifers bordering the Awash River (left bank) have been sunk in the Melka Hida Well Field located some 8 km south of Nazret just upstream of Wonji Bridge. These wells provide large quantities of water for the supply of Nazret town and some of them have large yields. It is known that the alluvial and other aquifers in this well field get active recharge from the bordering river. However, the amount of recharge and also the recharge condition need further specific investigation.

The alluvial aquifers in general are composite; and usually represent nonindurated deposits with materials ranging from gravel to clays. These are materials laid down by the action of the Awash river either on its channel or on the adjacent flood plains owing to channel flows and periodic over bank flooding. The gravels and sands form important aquifers characterized by high permeabilities; while the clay,silt and loam serve as aquitards or aquicludes forming semi-confined or confined conditions in some of the wells. The alluvials generally form multi-layer aquifer system along with the other aquifer materials (mainly pyroclastics and some basaltic flows) in the well field.

As well data reveal, the alluvial deposits show characteristic textural variation that, of course, can cause much heterogeneity in hydraulic properties. Vertical changes in grain size that corresponds to a pattern of change that is shown by a meandering system[9] can be observed. However, this generally upward fining trend is complicated by intercalations of various pyroclastic materials (mainly tuffs, ashes and pumice) and also volcanic sand. A cyclic sequence is particularly shown by the geological log of well number 12 (Fig.4-1c) at Melka Hida. Normal grading are also observed in other well logs but without the cyclic nature. The sand layers encountered in well numbers 10 and 11 at Melka Hida represent very good aquifer (Fig.4-1a,b).

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[9]Although Awash is not a fully established meandering river in the area, the deposits developed and their settings can generally be taken as that of a meandering system.

Generally, the alluvial sediments in the Melka Hida well field, according to the well logs by Manhasbot and Yirga (1989) have a thickness reaching up to 18 m near the river bank that decreases moving away from the river. Delineation of the alluvial aquifer is very difficult owing to the scarcity of data. But, again from the well logs, a maximum lateral extension of not more than 300 m from the river could be anticipated before these sediments wedge out. The aquifers in this well field form a separate system from the various aquifers found in the remaining part of the study area.

On the surface, however, the alluvial sediments are often composed of fine grained materials (clay and silt) especially on the flood plains (see map). This gives rise to a generally decreased infiltration capacity over those places and hence limited direct recharge from rain.

Other alluvial deposits in the study area occur in Mermersa stream channel and in the courses of other ephemeral streams. In the Mermersa stream bed the alluvium is composed of channel fill sands that occupied former troughs within the river bed. Small holes (pits) dug by the local people have been observed on this alluvium. These pits are used to collect water after even small rains and preserve it for some time because the deposit is already water bearing for most part of the year even in the dry season.

The lacustrine sediments in the study area in general show anisotropic permeability due to the variation in their size composition both from place to place and in depth. On the surface these sediments are considered to have low permeability for they are composed of different sizes (poorly sorted) with finer elements being dominant. However, in the southern part of the study area the sediments are mainly characterized by coarse grained volcanoclastic components and are considered as a very good aquifers. Many hand dug and bore wells tapping water from lacustrine sediment aquifers have been sunk in many places in the area.

4.2.2. Cinders, spatters and scoriaceous basalts

Cinders, spatters and scoriaceous basalts which, in the study area, usually form volcanic cones around central vents are generally highly pervious. As is shown in the geologic map they outcrop mainly in the eastern and southern parts of the area. These commonly fragmental materials exhibit both intergranular and fracture porosities. In some wells (Fig.4-4a) they have been observed to be important aquifers occurring with interbeds of other permeable units giving a high bulk permeability. They can also be considered as an important recharge zones in the outcrop area.

4.2.3. Porphyritic vesicular basalts

Vesicular basalts in general have high porosity due to the abundance of vesicles. But, since the vesicles are apparently unconnected these basalts often show low permeabilities unless they are cris-crossed by fractures, cracks, joints and/or are heavily weathered.

In the study area, the vesicular basalt unit tends to have variable permeabilities in different places. The outcrops which are found mainly in the southern and southeastern parts show weathering effect and also columnar jointing at places. As it is observed from log of the well at Deka Adi, north of Nazret, (Fig.4-3a) weathered vesicular basalt makes productive aquifer. However, in some wells the unit shows reduced primary porosity due to the presence of amygdules in the vesicles. Nevertheless, the unit as a whole can be qualitatively considered as having a moderate permeability in the study area. See also figure 4-4b.

4.2.4. Aphanitic basalt

From hydrogeological point of view two extreme varieties of the aphanitic basalt can be identified. The first ones are those basaltic rocks which are relatively dense, unfractured and may be unjointed; and the second heavily weathered and/or fractured. Whole spectrum between the two cases are believed to occur.

The fresh or poorly weathered and/or fractured basalts usually represent aquitards in many wells drilled in the study area (Fig.4-1a and 4-3a,b). The only surface outcrop of this basalt is found on top of kechema ridge.

Weathered and/or fractured zones of the aphanitic basalt unit are considered to have high porosities. These zones sometimes occur as mantle to massive aphanitic basalt bed rocks below them (Fig.4-1c). When occurring interlayered between relatively impervious layers these basalts form aquifers that may store significant amount of water (Fig. 4-1c,d and 4-4a,b). At depths where the groundwater level does not reach, these rocks may be taken as important passage ways for downward movement of water as recharge. Surface outcrops of this variety of basalts are very rare in the study area. A very small outcrop occurs just west of Nazret (see map). Other outcrops are observed in section and are not in a mappable scale.

4.2.5. Loose pyroclastic deposits

The main loose pyroclastic deposits occurring in the area include: pumice falls, ash flows, surges, unwelded tuffs and volcanic sand.

The ash flows and unwelded tuffs are generally characterized by high porosities but with low permeabilities. Hence, they act as aquicludes or as leaky beds in many wells. On the other hand, the pumice fall and the volcanic sand horizons are most important aquifers in the study area particularly at Melka Hida well field and in many hand dug wells east of Wonji Sugar Estate. Many wells sunk in this well field and in Wonji are tapping water from aquifers formed by these deposits (Fig.4-1). In this well field the deposits often occur as intercalations with other permeable units giving high bulk permeability.

The pumice falls consist of mostly lapilli sized pumice clasts which gave the deposits very high primary porosity and usually form loose deposits. Hence, having high permeabilities. In places when these deposits occur as interlayerings between main units (like in the ignimbrites and acidic flows) they can serve as pockets of water bearing zones. Surface outcrops are limited to the southern part of the study area.

The surges which are only outcropping in a limited extent in the southern part of the study area are characterized by mixture of various sized components in which the finer or muddy elements are dominant. This gives the deposits low permeability. However, the stratification which often is displayed by these deposits might give rise to a limited increase in the amount of permeability particularly in the horizontal direction. The volcanic sand forms important aquifers in the Melka Hida well field and also in other places in the area.

4.2.6. Lithic rich ignimbrites

The lithic rich ignimbrite unit which covers the relatively low lying area west of Nazret is characterized by abundance of pumice clasts and scarce welding. While this (presence of pumice) gives the unit certain amount of porosity, it is generally characterized by low permeability mainly due to the low degree of pore interconnectivity and to the scarcity of cracks, joints and/or fractures as field observation reveals.

4.2.7. Intensely welded ignimbrites

These ignimbrites include the ignimbrite unit which was previously identified as I_1, and which outcrops mainly to the west and southwest of Nazret, and the ignimbrite unit identified as I_3 which is product of the Gedemsa volcanics. Very limited surface outcrop (restricted to the southern part) of the later occurs in the study area. However, it was observed in some well logs (Fig.4-1b)

The intensely welded ignimbrites which usually form scarps to the west, southwest and northwest of Nazret is generally considered impervious having very limited permeability attributable to primary porosity. In some places (west of Nazret), however, the unit has been observed to be intersected by mainly vertical jointing having a width of up to 20 cm. Although some of these fractures (joints) are open giving the unit limited local permeability in the vertical direction, many of the joints happen to be closed by secondary mineral precipitation. In addition to this, it is generally believed that not only the frequency but also the aperture width of the joints decreases with depth. In spite of the fact that the general decrease of the aquifer properties of ignimbrites when they get weathered, weathered ignimbrite aquifers have been observed in some of the wells in the study area (Fig.4-2).

4.2.7. Rhyolitic lava flows and domes

In the study area, rhyolitic rocks mainly form domes and ridge. They represent rhyolitic flows of different age with associated interlayerings of obsidian and they are generally considered to be very poor aquifers. The rhyolitic domes northeast and southeast of Nazret neither show incision by faults (or fracturing) nor the rocks are weathered. They represent dense lava flows and, therefore, are considered impervious. The flow at Wogillo (southeast of Nazret) also behave likewise.

Although the flows that are forming Boku ridge are highly incised by a number of regional faults, the fractures could be closed not only with the accumulation of weathering products but also by the deposition of secondary minerals. The hydrothermal activity occurring in this place may facilitate the transportation and deposition of secondary minerals. It has been observed that cracks, joints and small fractures are scanty and widely spaced when present. On the other hand, no well log in the study area indicates any aquifer made up of these rocks.

The pyroclastic interlayerings, mainly the pumice falls, that have been occasionally observed in the flows south (Boku) and SE (Wogillo) of Nazret may represent pockets of pervious units. But they are not considered to be important.

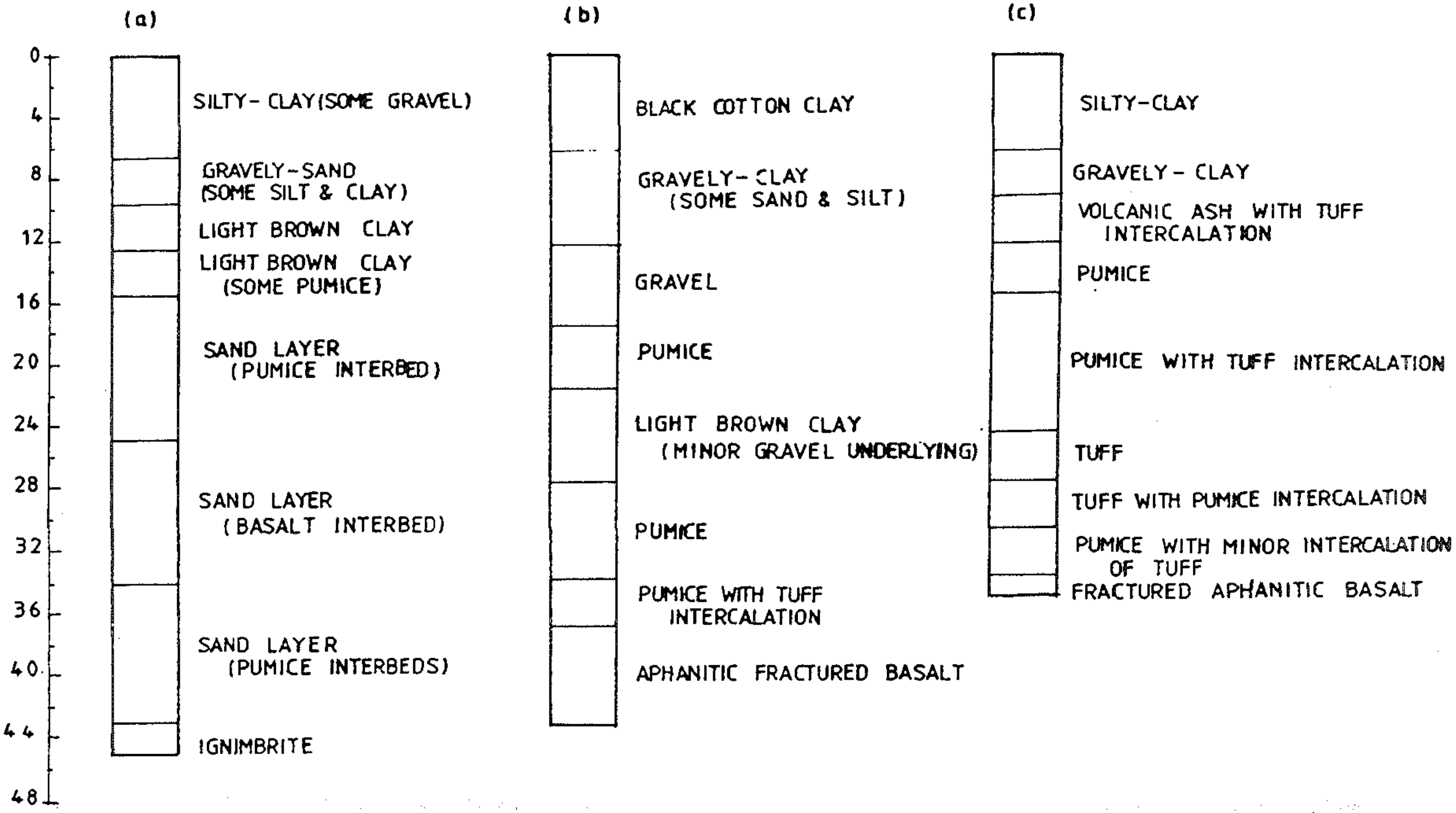


Fig.4-1 Lithiological Log of Well No (a) 10, (b) 12 & (c) 13 at Melka Hida, Nazret.
(Source: Menhasebo and Yirga. 1989Sc. 1:400)

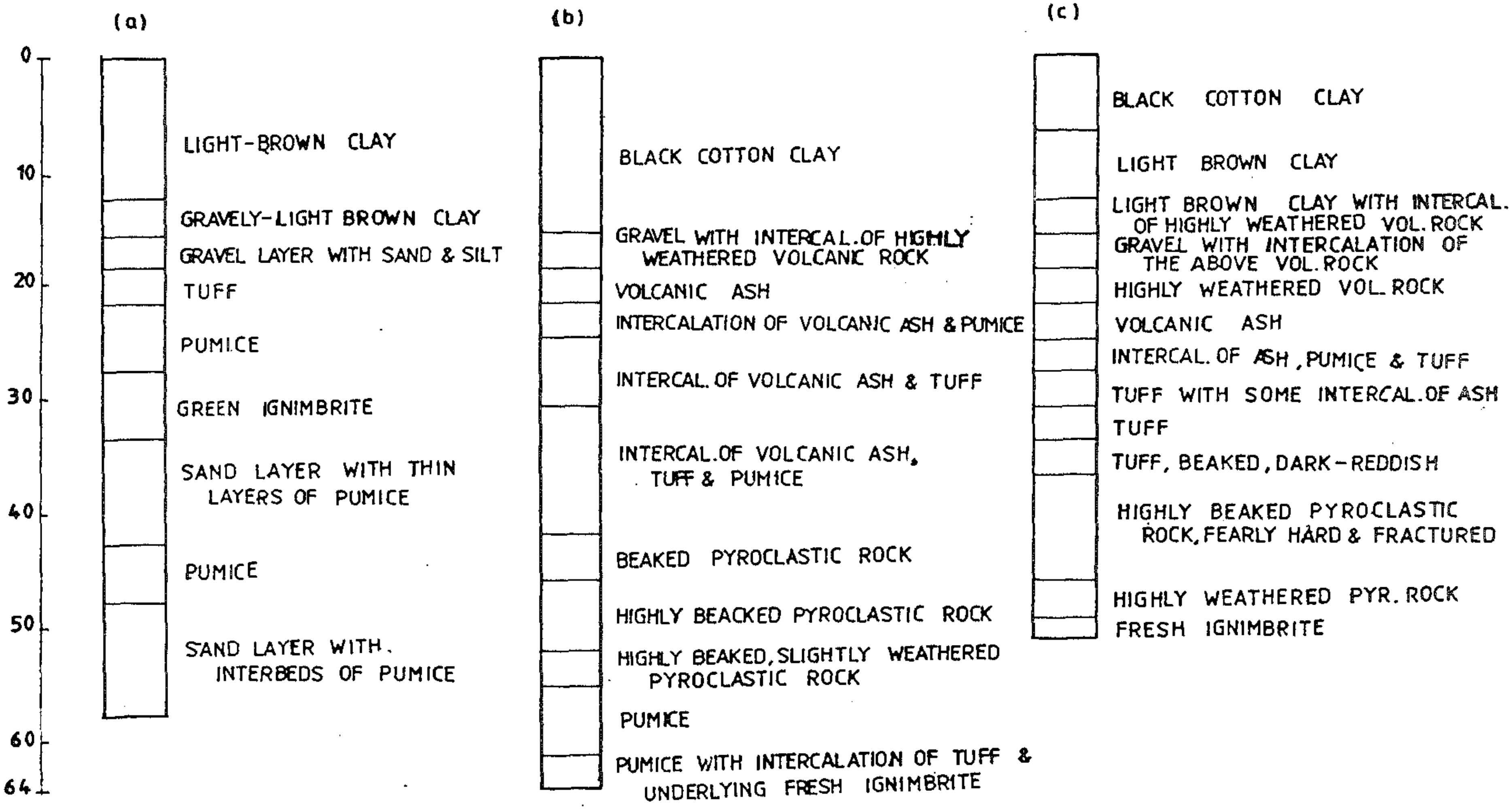


Fig. 4-2 Lithological Log of Well No (a) 11, (b) 15 & (c) 14 at Melka Hida, Nazret.
(Source: Devecon, WSSA, 1990 Sc. 1:525)

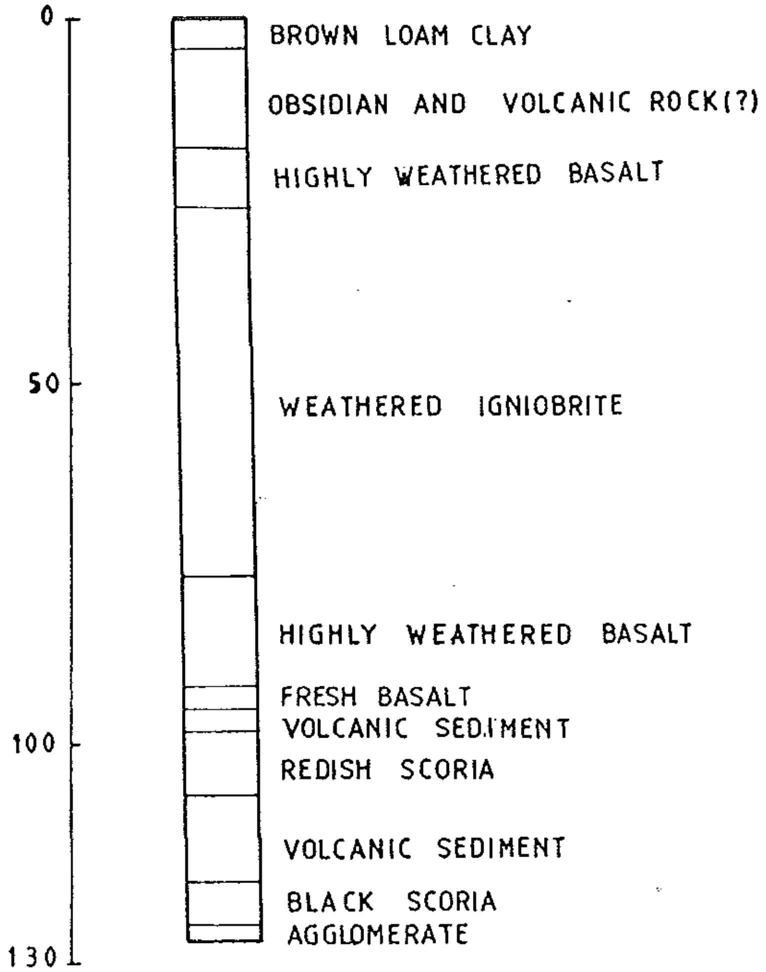


Fig. 4-3 Lithological Log of the Well at Wake Tiyo, Nazret.

(Source: Devecon, WSSA. 1990 Sc. 1:1000)

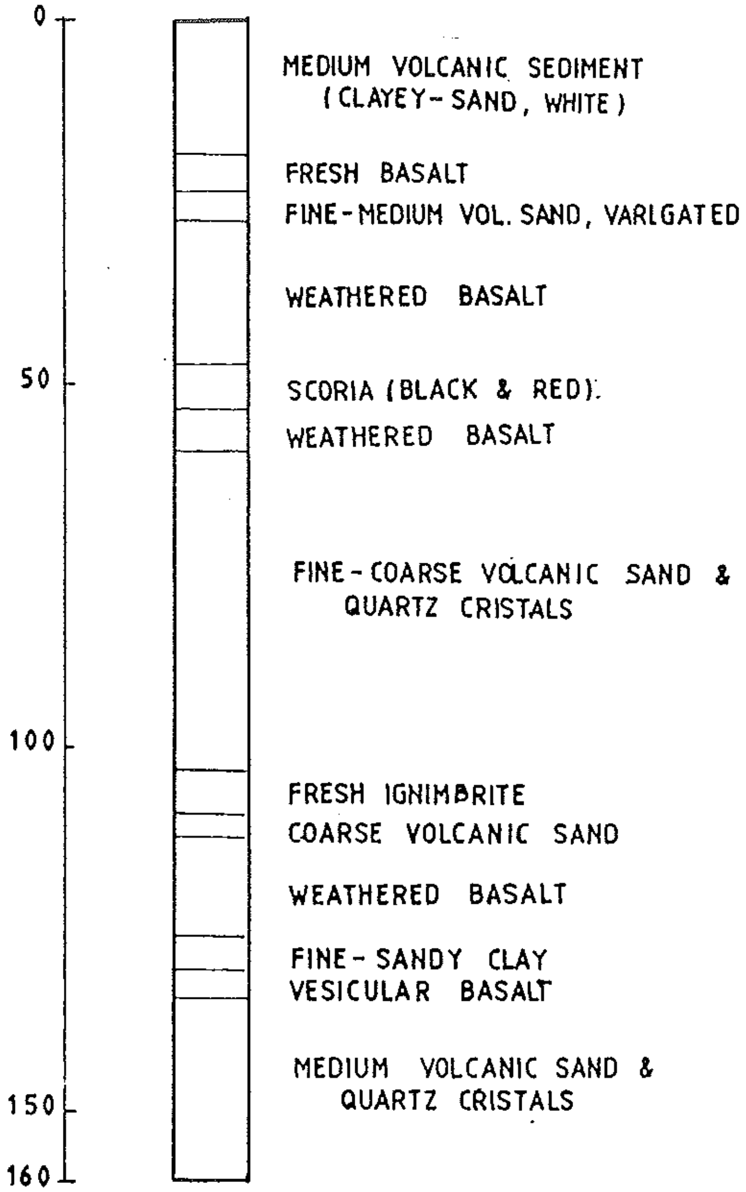


Fig. 4-4 Lithological Log of the Well at Wachu Lefa, Nazret.

(Source: Devecon, WSSA. 1990 Sc. 1:1000)

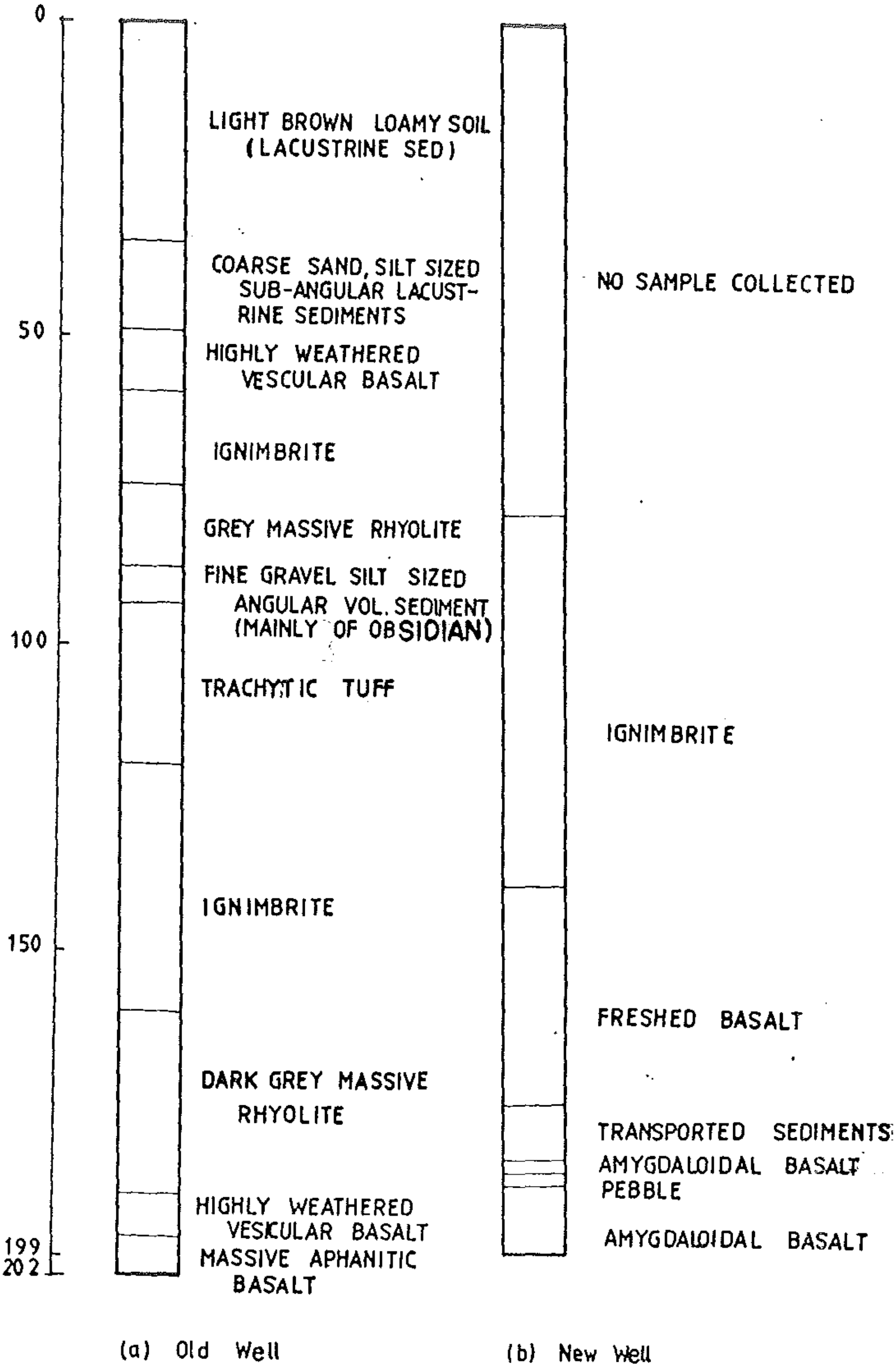


Fig. 4-5 Lithological Log of Wells at Deka Adi, Nazret.
Sourse: Devecon, WSSA 1990

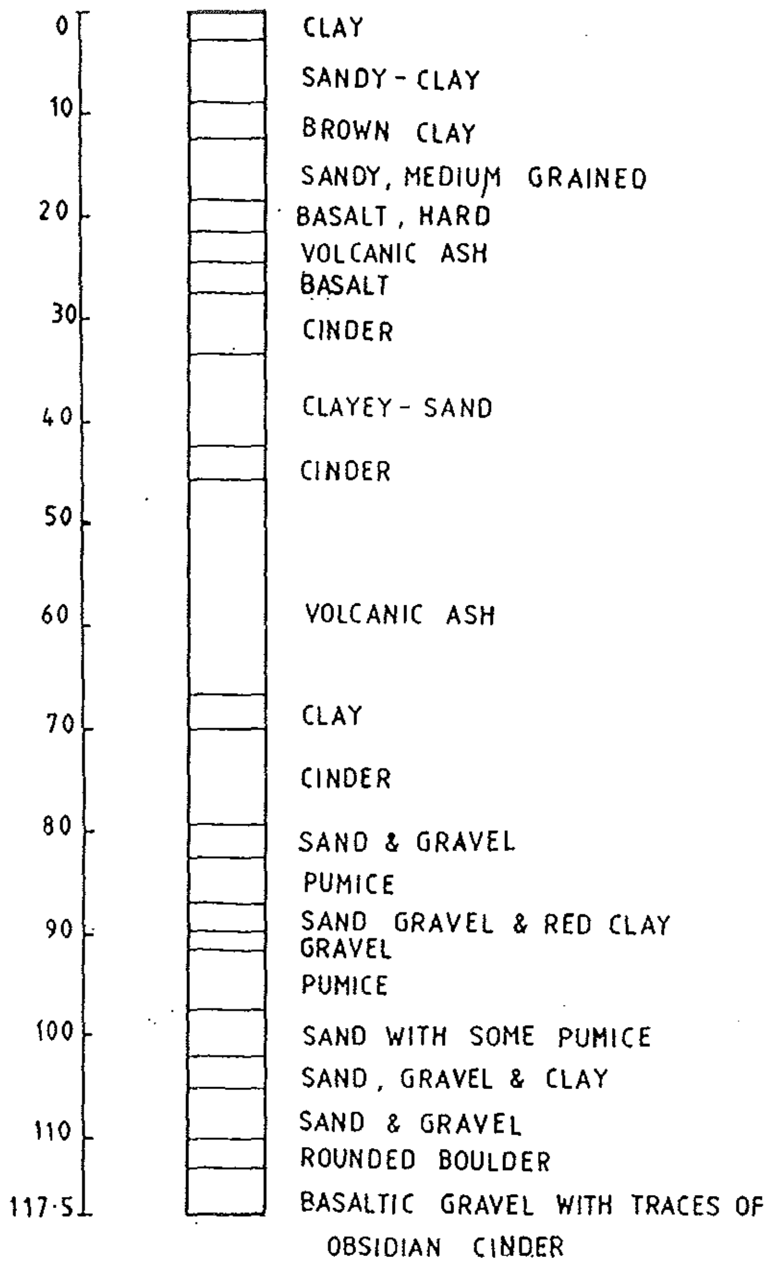


Fig. 4-6 Lithological Log of Well No 2 (Yilma Derisa), Nazret.

(Source: Devecon, WSSA. 1989 Sc. 1:750)

5. Well Hydraulics

5.1. General

Several bore and dug wells have been sunk in many places within the study area to supply Nazret, Wonji and surroundings. The water from these wells is used for various purposes (i.e., domestic, industrial and in few instances for irrigation).

Although more than 30 bore wells and large number of dug wells (particularly around Wonji) are known to exist within the study area, phreatimeteric measurement has been done only for limited number of wells owing to the fact that many of the wells are sealed (or have no piezometer) and to the brief observation period. It has, however, been tried to carry out measurements on those wells which are suitably distributed over the study area so as to help to construct groundwater contours on the hydrogeological map. Table 5.1a and b show the information on some selected wells in the area. No significant variation of depth to water level in the wells is observed when the values depicted in the tables are compared to some values previously determined in the same wells.

In the study area depth to groundwater level generally ranges from few meters (as small as 3 m) to more than 170 m below ground level. In the bore wells it ranges from few meters (as small as 5 m) in the southern part of the area (aquifers bordering Awash and those found around Wonji) up to 175 m in its northern part (Deka Adi well No.1). The depth generally decreases towards Awash river both from the north and from the south of it. The rate of decrease of depth with distance is higher in the areas north of Awash river than to the south (around Wonji) and hence a higher hydraulic gradient is generally expected in the former case than the later.

Yield of the bore wells varies widely from place to place and it ranges from as low as about 1 l/s (EFTC well No.2) to 12 l/s (Table 5.1a). Higher yields were generally observed for the wells penetrating the shallow aquifers in the southern part of the area. Again, the specific yield of the wells also show significant variation even among wells with similar yields and/or are located adjacently (as exemplified by the wells at Melka Hida) mainly due to the wide variation of lithology of aquifers both from place to place and within short distance in the same place.

The major proportion of the present water supply for Nazret town is obtained from the 15 wells[10] placed at Melka Hida well field. Many governmental and other organizations have their own wells.

Almost all the hand dug wells found in the study area are located in its southern part particularly around Wonji. For instance, it can be said that almost every other household at Wonji Kuriftu village have got domestic dug wells in their compound. These is mainly due to the shallow depth to the groundwater level in these place. Depth to groundwater level in the dug wells range from about 3 m (at Gergedi hot spring area) to more than 10 m below the ground level (Table 5.1b). Most of these hand dug wells are poorly constructed and mainly penetrate various alluvial and lacustrine sediments together with loose pyroclastic pumice fall and scoriaceous basalt

[10] The remaining wells are located within the Municipal boundary of the town.

(cinders) aquifers. They are not expected to have high yields due to the poor construction and their small depth (and hence smaller penetration to aquifer materials). In most cases the water from these wells is used for washing and cattle watering purposes.

Table 5.1a Data on selected bore wells at Nazret and surrounding

Ref. No.	Code/name	Location	Owner	Date drilled	Elevation (m)	Total depth(m)	SWL (m)	Yield (l/s)	Water supply to
BS_{14}	No.1(new)	Deke Adi	WSSA	Mar.,1988	1700	199	175	2.0	Nazret Town
BS_{15}	Wachu lefa	Wach Lefa	Public	1986	1500	160	114	2.0	Local Peasants
BS_{8}	Ras Hotel	Nazret	Ras	1966	1620	134.9	100	3.0	Swimming pull
BS_{2}	EFTC, No.2	Nazret	EFTC	-	1620	196	150	1.25	Workers
BS_{7}	Wake Tiyo	Wake Tiyo	Public	Aug.,1986	1560	127	100	5.0	Local Peasants
BS_{3}	Yilma D., 2	Nazret	WSSA	Dec.,1966	1600	134	102	2.5	Nazret Town
BS_{9}	No.2	Melka Hida	WSSA	1947	1547	59	14.53	2.0	Nazret Town
BS_{10}	No.4	Melka Hida	WSSA	1954	1540	68	16	2.0	Nazret Town
BS_{4}	No.7	Melka Hida	WSSA	Jan.,1988	1540	103.6	13.57	9.2	Nazret Town
BS_{16}	No.10	Melka Hida	WSSA	Mar.,1988	1540	45	10.59	12.0	Nazret Town
BS_{11}	No.11	Melka Hida	WSSA	Mar.,1988	1540	50.5	11.43	12.0	Nazret Town
BS_{17}	No.12	Melka Hida	WSSA	Mar.,1988	1539	43	11.24	12.0	Nazret Town
BS_{18}	No.9	Melka Hida	WSSA	1978	1539	56	12.25	2.0	Nazret Town
BS_{19}	Village A	Wonji	Sugar Fac.	1962	1540	43.87	5.67	5.0	Factory workers
BS_{20}	Village B	Wonji	Sugar Fac.	1962	1540	33.0	12.0	3.0	Factory Workers
BS_{21}	Camp G	Wonji	Sugar Fac.	-	1540	-	5.49	3.0	Factory Workers
BS_{22}	Camp F	Wonji	Sugar Fac.	-	1540	46.48	7.77	3.0	Factory Workers

Table 5.1b Data on some hand dug wells of the study area.

Ref. No.	Location	Depth	Water Level (m.a.g.l)[a]	Elevation	Use
DS_1	Around Paper Mill	10.87	10.37	1540	washing and other
DS_2	Around Paper Mill	9.7	7.35	1542	washing and other
DS_3	Around Paper Mill	9.8	7.44	1540	washing and other
DS_4	Wonji Gefersa	7.0	6.39	1540	washing and other
DS_5	Wonji Gefersa	11.0	10.72	1545	washing and other
DS_6	Wonji Gefersa	7.5	6.34	1540	washing and other
DS_7	Wonji Gefersa	9.0	6.06	1540	washing and other
DS_8	Wonji Gefersa	11.9	9.96	1544	washing and other
DS_9	Wonji Gefersa	14.3	10.66	1545	washing and other
DS_{10}	Wonji Gefersa	10.8	9.80	1545	domestic
DS_{11}	Gergedi	4.0	3.75	1540	(for irrigation)[b]
DS_{12}	Gergedi	4.0	3.50	1540	domestic

a meter below ground level

b very small scale cultivation in a private compound

Groundwater contours have been constructed for some part of the area depending on the distribution of wells and available data. Based on depth to groundwater level the study area can be broadly divided in to two; these are a) those places underlain by shallow aquifer zones which include mainly the southern part of the area, that is, the area bordering Awash River and around Wonji and b) those places with deeper aquifers which include almost all the remaining portion of the study area. Hence, a groundwater contour interval of 1 meter (even half meter in few instances) and an interval of 10 meter are used over those places respectively on the hydrogeological map. Here it should be noted that the shallow and the deeper aquifers represent different system of aquifers.

From the groundwater contours and from topographic observations, at least four major groundwater basins could be identified in the area. These can be named as a) Wachu Lefa

(Eastern), b) Wake Tiyo (Southeastern), c) Nazret-Wonji (Central), and d) Western basins. Some of these basins seems to be interconnected. However, it is difficult to clearly identify the exact boundaries of these and probably other subsurface basins in the area apparently due to the complexion created by the intense faulting.

5.2. Well hydraulics

In the evaluation of groundwater resource potential of an area, pumping tests offer the most powerful method in analyzing the fundamental characteristics of aquifers. Measurements made during these tests permit determination of the aquifer constants, that are, transmissivity (T), hydraulic conductivity (K) and storage coefficient (S).

The data on constant rate pumping test which have been conducted for some of the wells in Nazret (mainly at Melka Hida well field) are shown in annex 7 to 12.

Since the pumping tests were conducted without observation well(s) or piezometer(s) (i.e., are single well tests), Theis non-equilibrium formula could not be applied to calculate the storage coefficient of the aquifers. Instead the aquifer constants T and K only were determined by graphical analysis of drawdown using Jacob's straight line method. Thus, transmissivity was calculated from the pumping rate (Q) and the slope of the time-drawdown curve (Δs) or of the residual drawdown plot ($\Delta s'$) by using equation 5.1 and the hydraulic conductivity was determined from the relation $K = T/b$, where b represents saturated thickness of aquifers.

$$T=\frac{2.3}{4\pi}\frac{Q}{\Delta s'}=0.183\frac{Q}{\Delta s'} \qquad 5.1$$

Where:

T = Transmissivity in m^2/d

Q = Pumping (discharge) rate in m^3/d

$\Delta s'$ = Change in drawdown over one log cycle

The results of the pumping test analysis for the different wells are portrayed in figure 5.1 to 5.6. Here, even though the residual drawdown plot for a pumped well (drawn from the time-drawdown measurements taken during recovery period) provide more accurate results than its time-drawdown plot (drawdown from the time-drawdown measurements taken during pumping period), both curves were used in the analysis and evaluation of the pumping test data on the present wells. However, T and K values determined by the Jacob's recovery method mainly are considered to be justified.

The following is interpretation of the results from Jacob's graphical method for each of the wells. Interpretations are mainly based on the literatures of Driscoll (1986), and Kruseman and de Ridder (1990).

Well-10 (Melka Hida):

The well was pumped at a rate of 12 l/s or 1036 m^3/d and the drawdown corresponding to 2865 minutes or 48 hrs of pumping is 10.72 m.

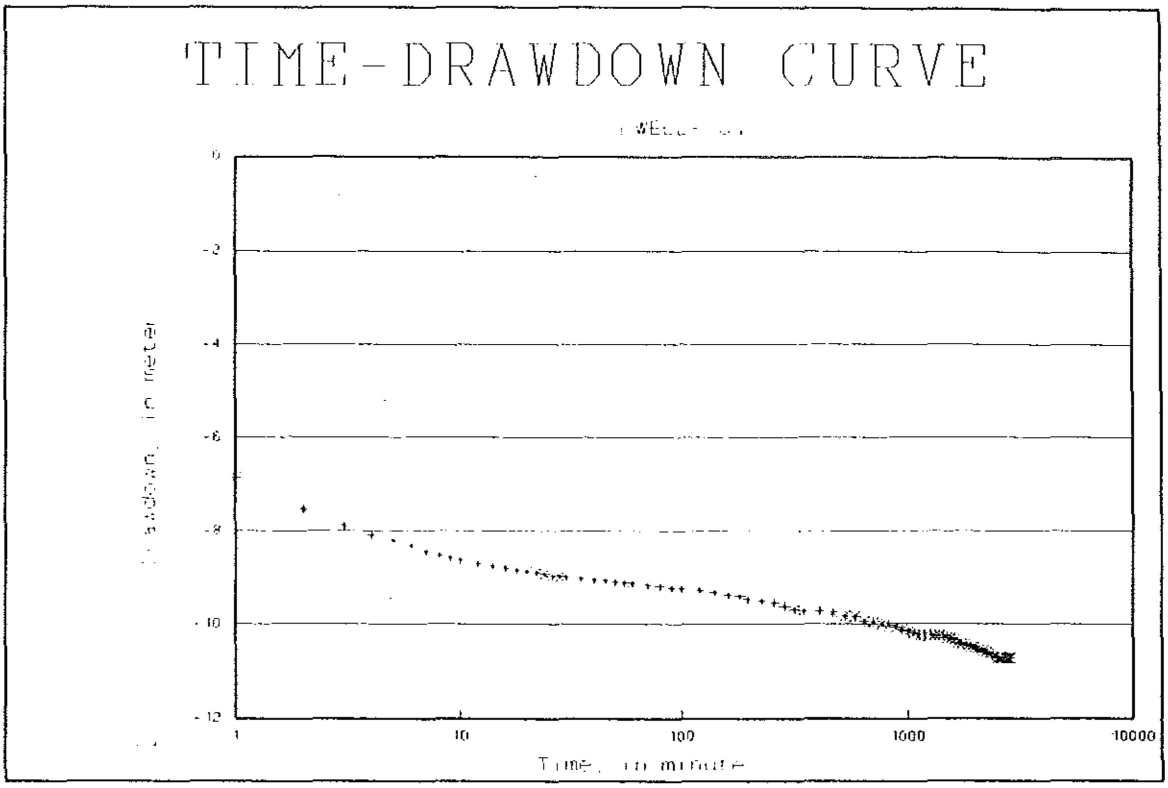
Evaluation of the data by Jacob recovery method (Fig. 5.1a and b) indicates that a transmissivity (T) of 364.87 m^2/d and hydraulic conductivity (K) of 21.15 m/day characterizes the aquifer(s). Specific capacity after almost 48 hrs of pumping is calculated to be 96.716 $m^3/d/m$ or 4.03 $m^3/hr/m$.

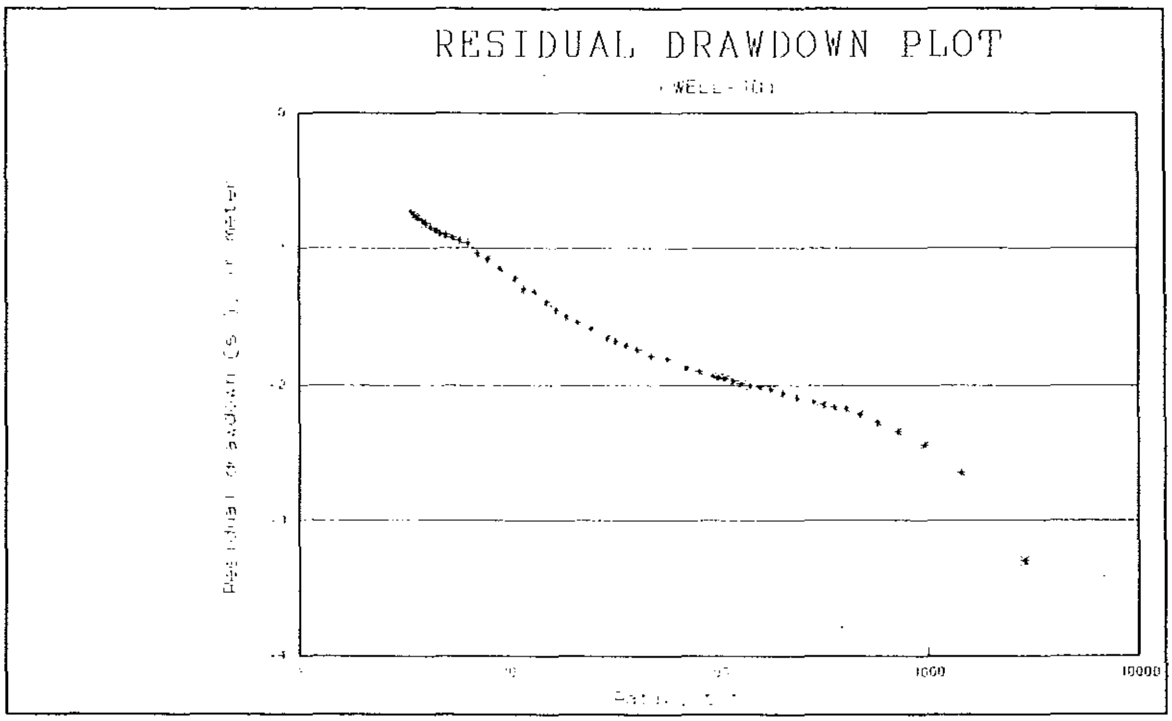
The values of T and K were obtained on the basis of the slope of the later part of the residual drawdown plot to avoid positive boundary effect. The time-drawdown measurements and the time-recovery measurements provide similar T and K values for this well when computed using Jacob method.

Early portion of the pumping (the first few minutes) shows effects of casing storage on the time-drawdown curve. While for the later time data the curve reflects recharging boundary effect on the drawdown. This is indicated by the break in the drawdown slope at t value of about 2200 minutes. That is, the slope becomes flatter when recharge to the aquifer occurred. Hence, the small horizontal leg on the curve represents the stabilized drawdown at 10.72 m (Annex 7a) when recharge within the zone of influence of the pumped well equals the rate of discharge of the well.

The recharge to the aquifer (s) is also evidenced by the shape of the early part of the residual drawdown plot (Fig. 5.1b). This part of the curve indicates large intercepts at zero drawdown (if a straight line is extended) which is typical of a recharging effect. The fast recovery to the original static water level during relatively shorter time in the early portion of the recovery period (almost 80% in the first 5 minutes) is, therefore, brought about by recharge.

In general, in light of the above discussion , one can conclude that a recharging boundary was encountered after approximately 2200 minutes or 40 hrs continuous pumping of the well. And, the obvious recharge source to the well is Awash river located about 25 m away.





5.1. Time-drawdown (a) and Residual drawdown (b) plots of Well-10.

Well-11 (Melka Hida):

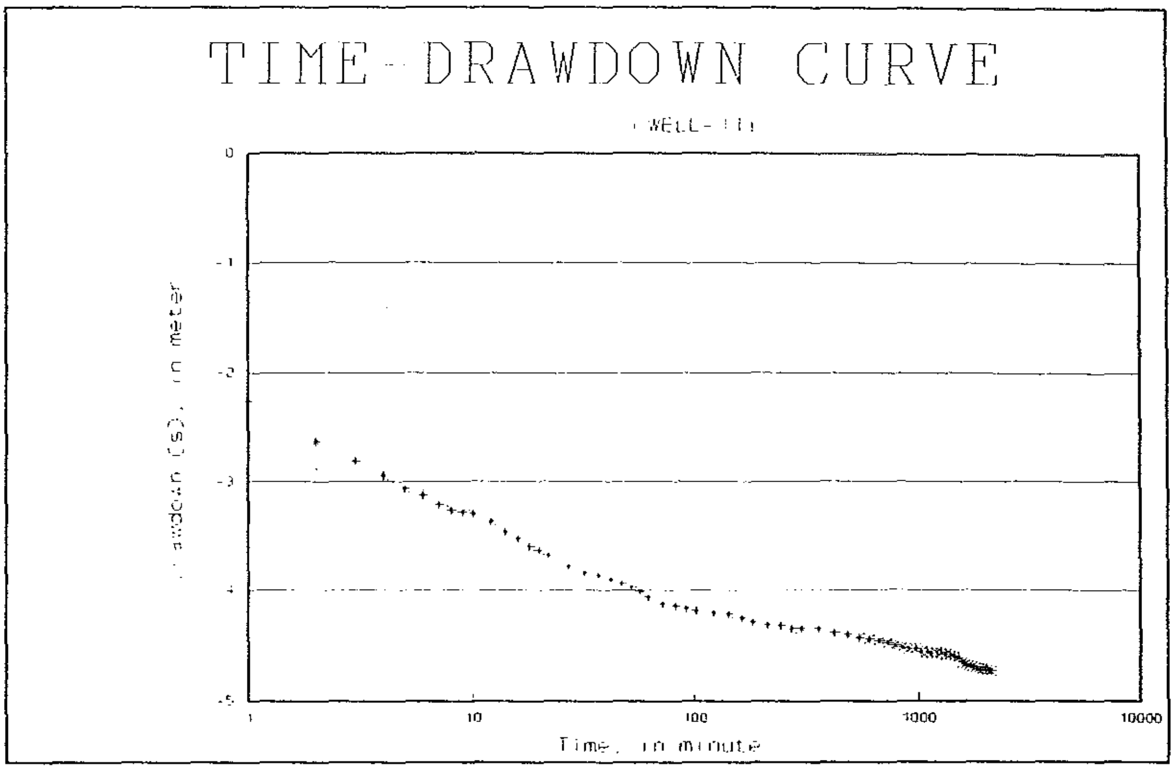
The well was pumped at a rate of 12 l/s or 1063 m^3/d and the drawdown corresponding to 2100 minutes or 35 hrs of pumping is only 4.73 m.

Evaluation of the data by the Jacob recovery method (Fig. 5.2b) gives a transmissivity (T) of 474 m^2/d and hydraulic conductivity of 27.50 m/day to the aquifer. Specific capacity after 35 hrs of pumping is calculated to be 219.19 $m^3/d/m$ or 9.13 $m^3/hr/m$.

Similar values for the aquifer constants were obtained by the computations using Jacob method of both the time-drawdown and recovery measurements.

The graphical interpretation of the time-drawdown measurements (Fig. 5.2a) indicates that recharge effect occurs after about 900 minutes of continuous pumping. However the recharge rate is some how less than the pumping (discharging) rate as shown by the flattened, but not horizontal, later portion of the time-drawdown curve. The effect of recharge is also evident from the residual drawdown plot (Fig. 5.2b) represented by the steepening of the curve for early recovery period data. The recharge source is, of course, the Awash river located 30 m far from the well.

The residual drawdown plot also shows the effect of limited aquifer extent. This is explained by the fact that when the later part of the residual drawdown plot is extended to the left it shows an incomplete recovery, i.e., a residual drawdown of about 0.75 m as t/t' approaches 1. Here it should be remembered that limited extent of aquifer and aquifer recharge account for opposite effects on the time drawdown curve. That is, the former causes steepening of the curve while the later causes flattening. Thus, the two effects could have overlapped in this case and, hence, one could possibly expect a larger recharge effect than is indicated by both the curves.



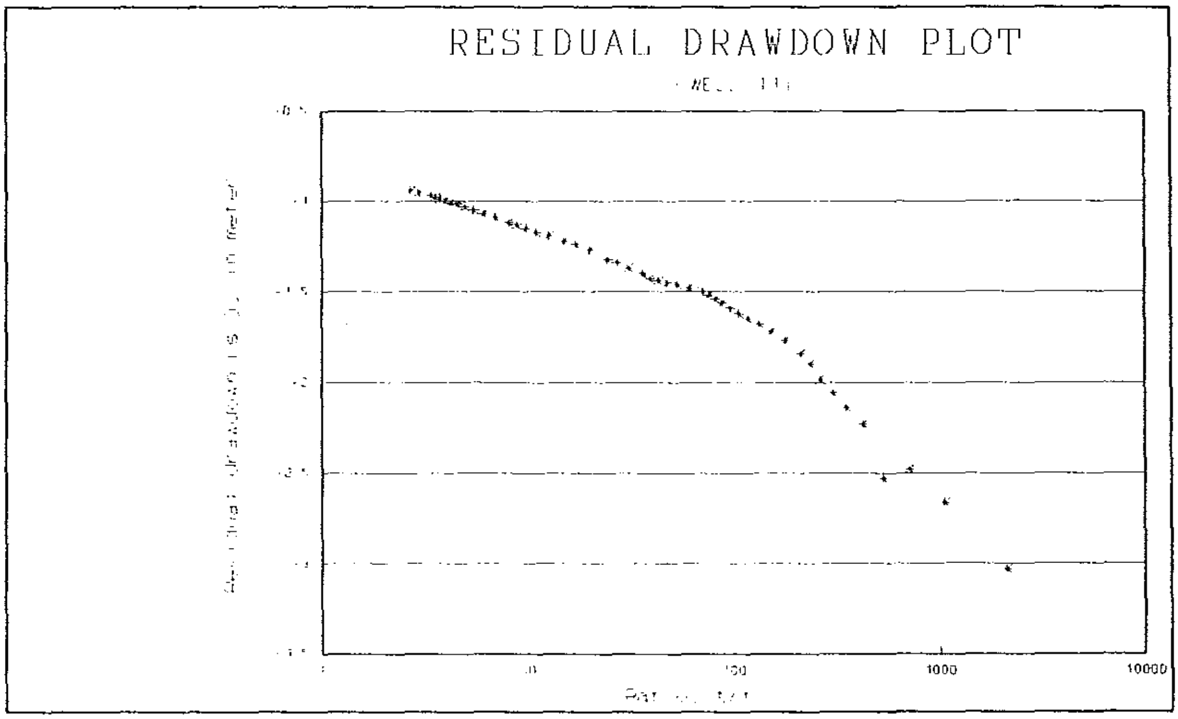


Fig. 5.2. Time-Drawdown (a) and Residual drawdown (b) plots of well-11.

Well-12 (Melka Hida):

The well was pumped at a rate of 12 l/s or 1063 m^3/d and the drawdown corresponding to 970 minutes or 16 hrs of pumping is 22.72 m.

Evaluation of the data by the Jacob recovery method (Fig. 5.3b) gives a transmissivity (T) of 441.23 m^2/d and hydraulic conductivity of 25.58 m/day to the aquifer. Specific capacity after 16 hrs and 10 minutes of pumping is calculated to be 45.63 $m^3/d/m$ or 0.76 $m^3/hr/m$. However, these values are expected to be less accurately determined due to the expected low discharge rate during the test.

Further interpretation of the test data for the well indicates that three different slopes are evident in the time-drawdown curve (Fig. 5.3a). The first slope represents test data of early pumping in which casing storage has affected the drawdown and hence are not valid when using the Jacob technique. The second and the middle slope which is almost horizontal may represent the true aquifer characteristics. However, The very low drawdown (the flatter slope) can be interpreted in two different ways, that is: a) if the aquifer is in hydraulic continuity with the nearby river Awash, the slope may reflect recharge from the river during pumping starting from early stages of the pumping. Additional recharge is also expected from the leaky clay layer. The later part of the curve (the third slope), hence, could be interpreted as representing negative boundary effect like impervious rock on the other side of the recharging river; and b) If the aquifer is not in hydraulic continuity with the river, starting from early stages of pumping, this part of the curve could represent lower rate of discharge from the well. The later part of the curve could then be interpreted as a change in the hydraulic properties of the aquifer and/or a negative boundary effect.

But, from the position of the well (i.e., 200 m away from the river) and the nature of the deposits in the well field, the second interpretation seems more realistic particularly for the early part of pumping. Nevertheless, recharge is expected especially in the later pumping periods and its effect on the curve could be overlapped with that of the low pumping rate. This is confirmed by the curves of well-13 (Fig. 5.4a and b) which is sunk into a similar aquifer material and found almost at the same distance away from the river. Pumping test data from these well shows a recharge effect approximately after about 2500 minutes of continuous pumping.

The residual drawdown plot also reflects similar effect indicated by particularly very fast recovery (90% recovery in the first one minute) almost close to the original static water level and this could be due to the combined effects of the low pumping rate and the possible recharge from the river.

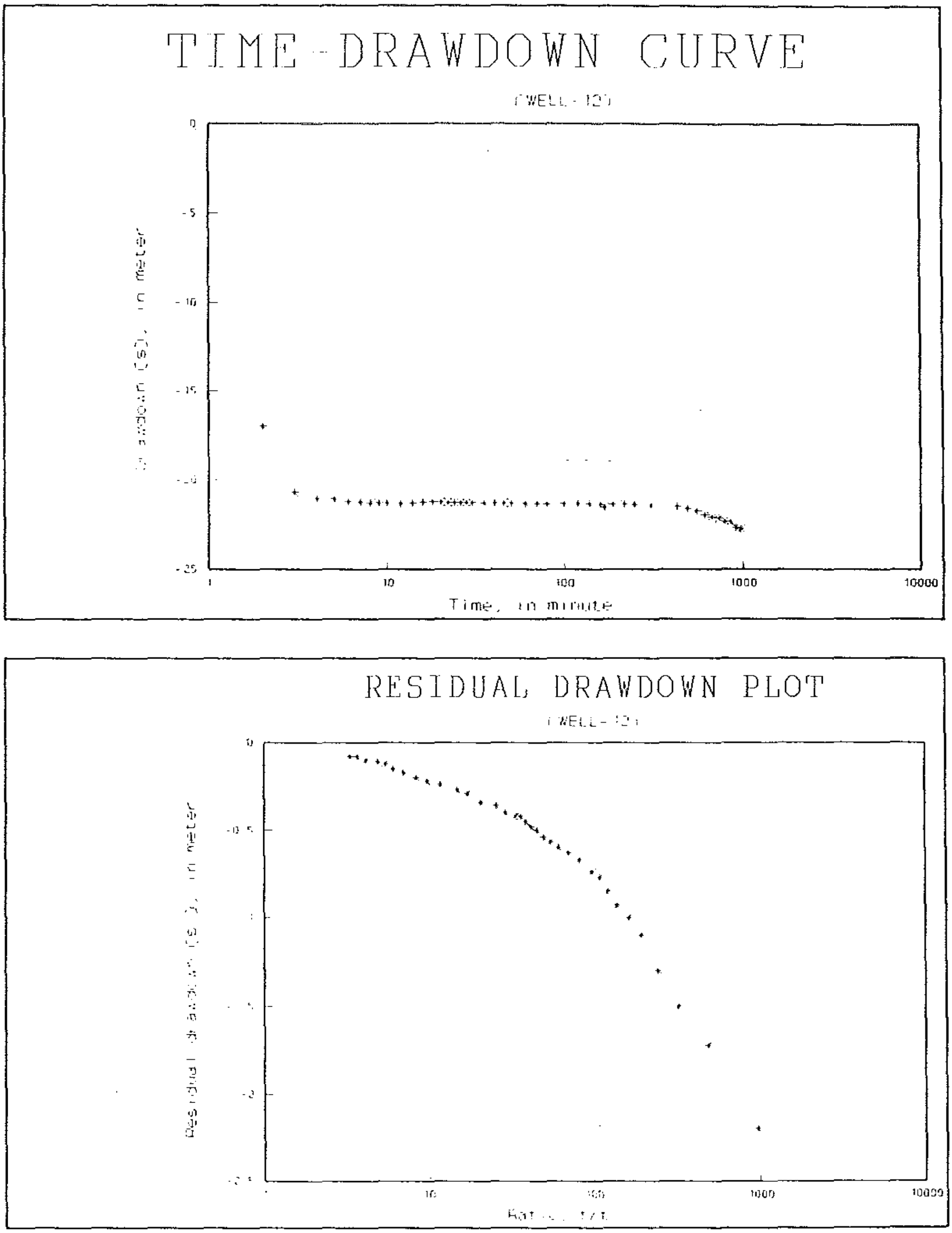


Fig. 5.3. Time-Drawdown (a) and Residual Drawdown (b) plots of Well-12.

Well-13 (Melka Hida):

The well was pumped at a rate of 12 l/s or 1036 m^3/d and the drawdown corresponding to 2850 minutes or 47 and 1/2 hrs of pumping is only 3.03 m.

Evaluation of the data by Jacob recovery method (Fig. 5.4b) indicates that a transmissivity (T) of 863.41 m^2/d and hydraulic conductivity (K) of 50 m/day characterizes the aquifer(s). Specific capacity after 47 and half hrs of pumping is calculated to be 342.18 $m^3/d/m$ or 5.7 $m^3/hr/m$.

More than half of the total drawdown was attained during the first five minutes and the pumping did not permanently increased the drawdown throughout the whole pumping period. Instead the drawdown has shown stability during two different stages of the test pumping. The first is after 1170 minutes of pumping at drawdown of 2.92 m for about 540 minutes (9 hrs) which was followed by a slight increase in the drawdown of only about 10 cm in 840 minutes (14 hrs). After this, the drawdown resumed stabilization at 3.03 m till the end of the pumping period. The first equilibrium condition may represent a recharge by vertical leakage from possibly saturated volcanic ash (with pumice intercalation) and/or gravely clay layers above the aquifer tapped by the well (Fig. 4.1c). The second equilibrium condition most probably corresponds to the time when the cone of depression around the well extends to a distance where it intercepts the river Awash, found 200 m far, (which is the most likely source of recharge) after about 2500 minutes since pumping began.

The recharge condition corresponds to the steepening part of the residual drawdown plot which represents the early stage of recovery.

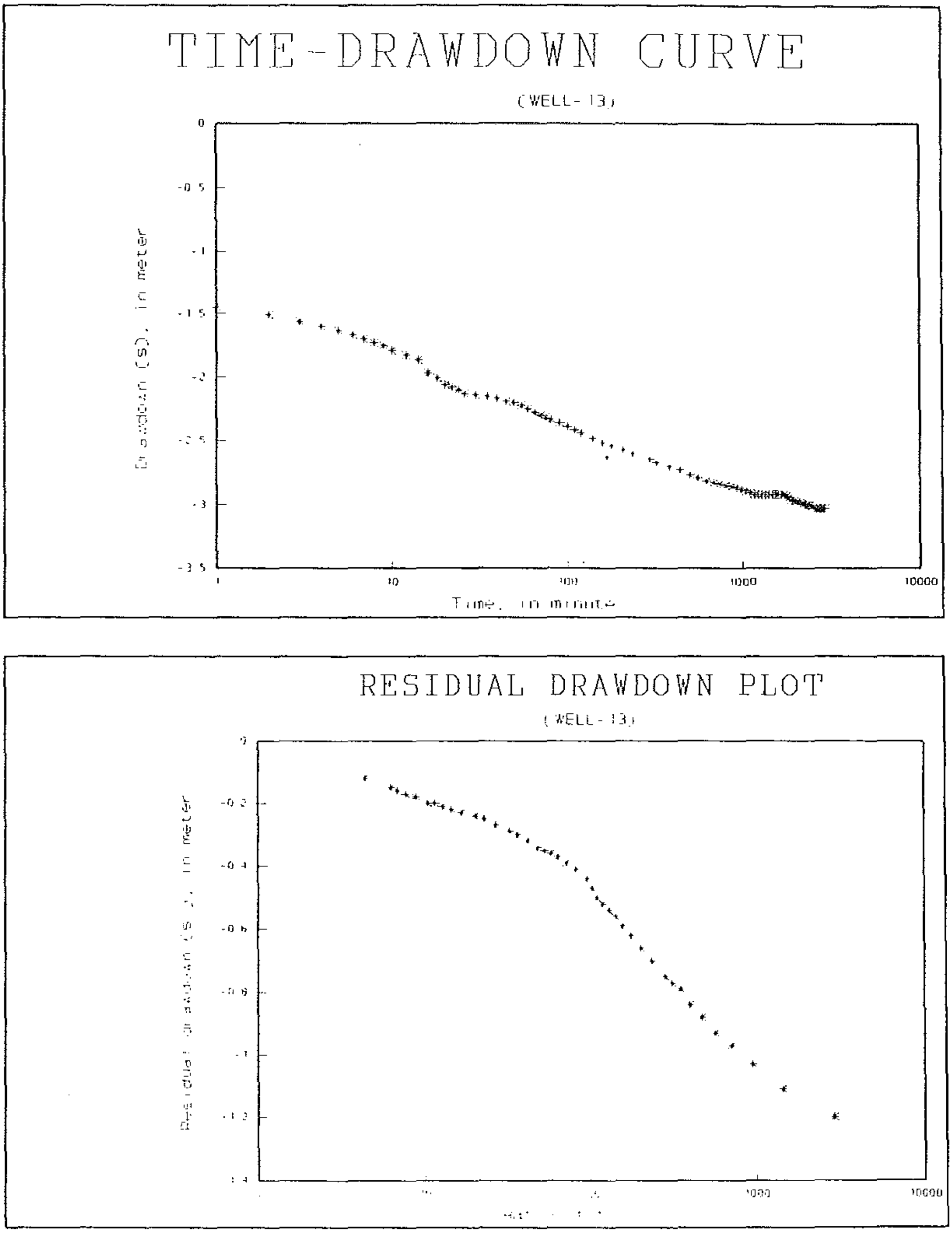


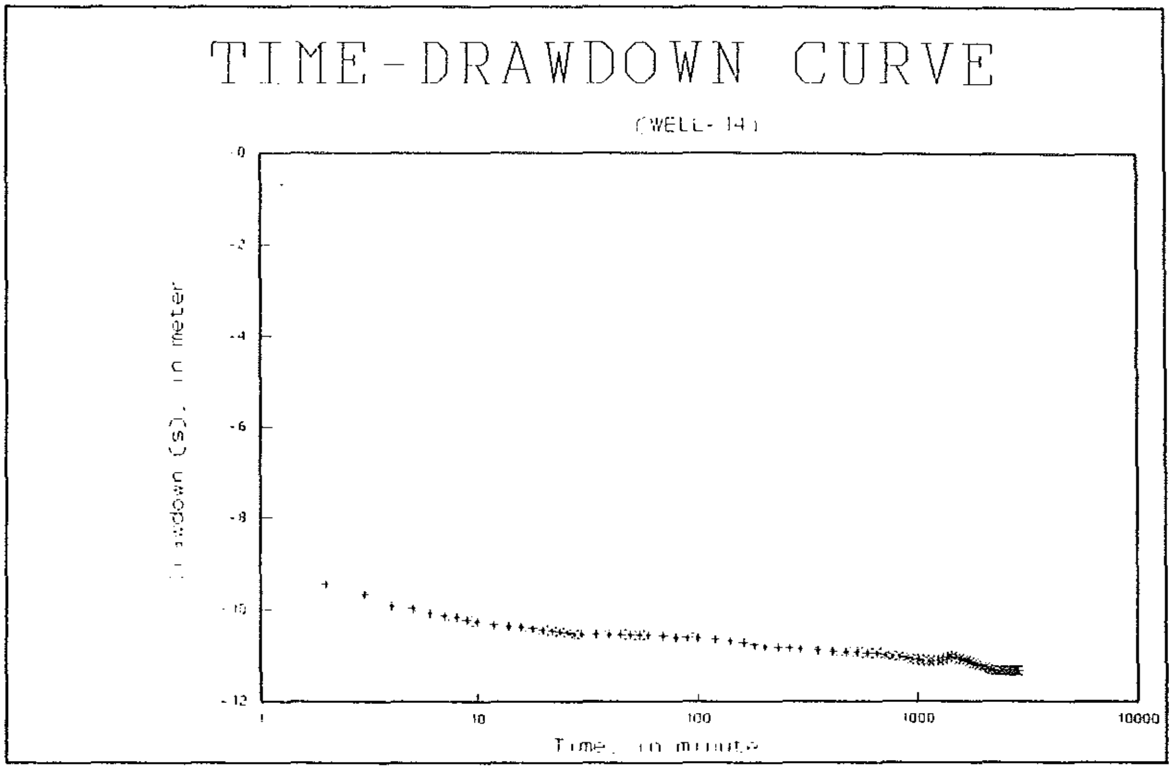
Fig. 5.4. Time-Drawdown (a) and Residual Drawdown (b) plots of Well-13.

Well-14

The well was pumped at a rate of 12 l/s or 1036 m^3/d and the drawdown corresponding to 2870 minutes or about 48 hrs of pumping is only 11.33 m. Except in the earliest part of the test which is most likely affected by casing storage, the well in general shows small drawdown increases as pumping proceeds. That is, of 11.33 m drawdown during the given pumping period, drawdown of about 9.0 m was attained only in the first one minute.

Evaluation of the data by Jacob recovery method indicates that a transmissivity (T) of 1355.2 m^2/d and hydraulic conductivity (K) of 78.56 m/day characterizes the aquifer(s). Specific capacity after about 48 hrs of pumping is calculated to be 91.51 $m^3/d/m$ or 1.5 $m^3/hr/m$.

The water level in the well stabilized at 11.33 m drawdown after approximately 2270 minutes (Annex 11a) of continuous pumping indicating condition that recharge within the zone of influence of the pumped well equals the rate of discharge (pumping). This is clearly portrayed by the later portion of the time-drawdown curve (Fig. 5.5a) in which a horizontal leg is evident, and the early portion of the residual drawdown plot (Fig. 5.5b) which shows a very fast recovery particularly in the earliest part of the recovery period (i.e., 90% recovery in the first one minute). The well reaches a nearly complete recovery only after 200 minutes from the pump stoppage. The prominent recharge source, like for the other wells in the vicinity, is Awash river found about 25 m away from the well. Minor recharge may also come from the leaky clay layers.



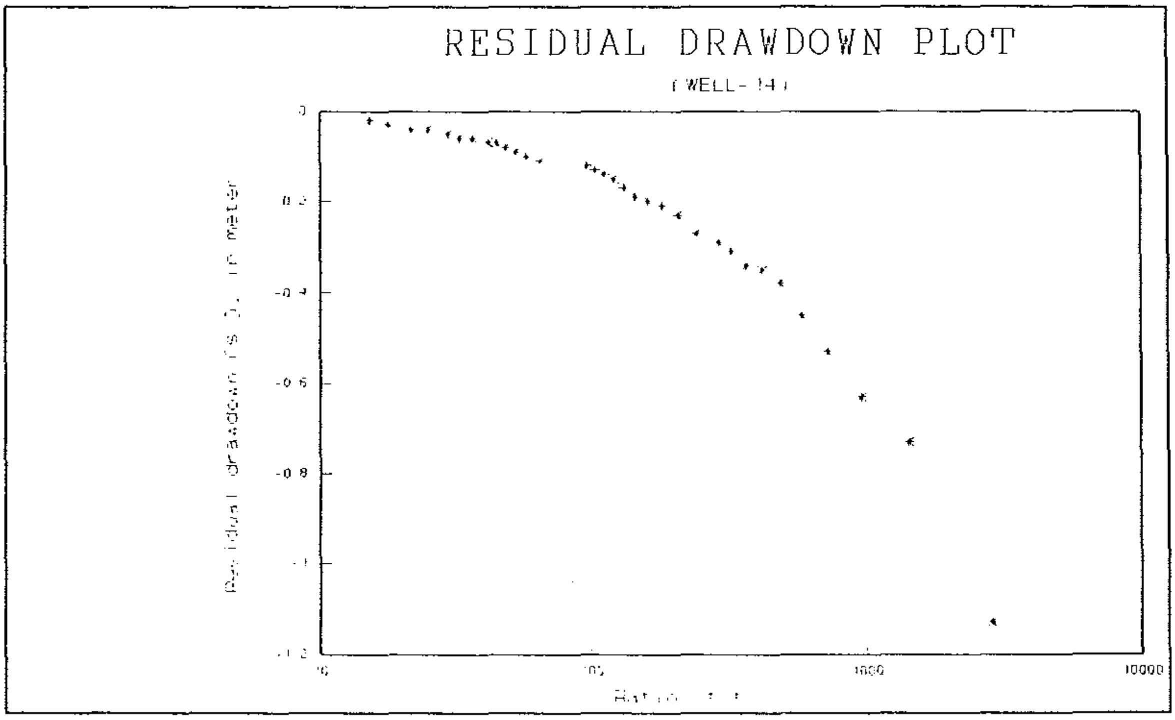


Fig. 5.5. Time-drawdown (a) and Residual Drawdown (b) plots of Well-14.

EFTC (Well-2):

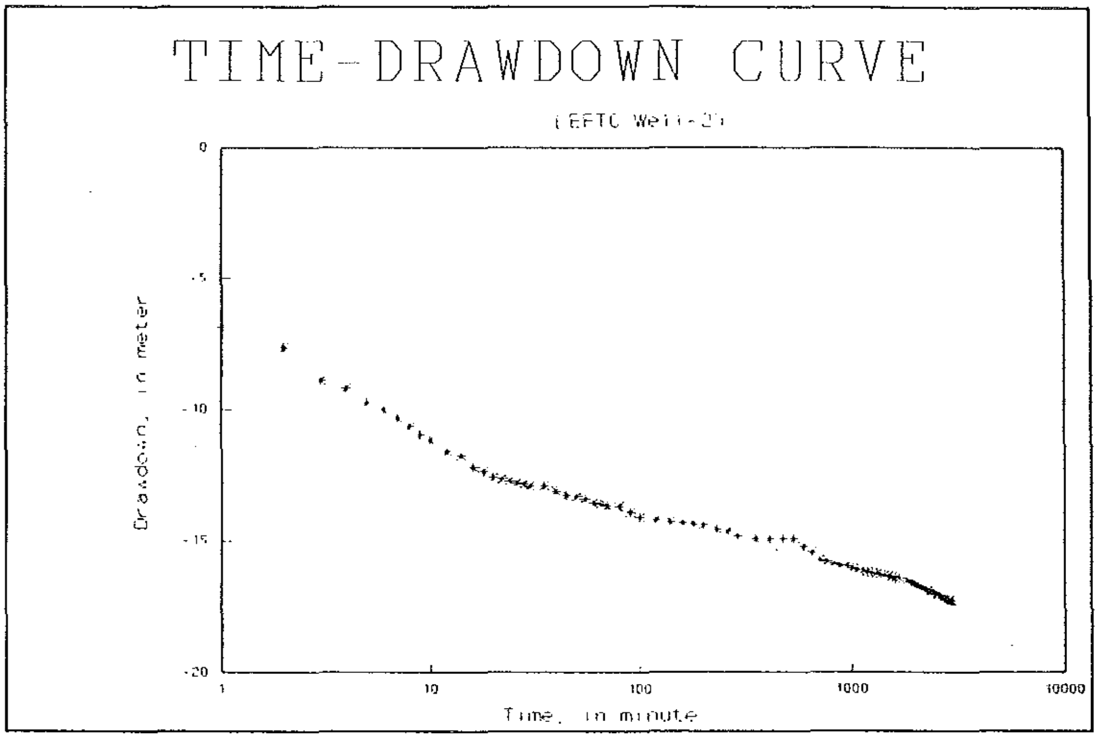
The pumping test was conducted at a constant rate of discharge of 1.2 l/sec or 108 m^3/d. The drawdown corresponding to 2980 minutes or 48 and 1/4 hrs of pumping is 17.28m.

No stabilization of the water level was attained in the well throughout the pumping period implying no possible recharging boundary within the zone of influence of the pumped well at least for the indicated pumping period. The recovery after 120 minutes from the stoppage of the pumping was observed to be 97.10%. No fast recovery, particularly in early recovery period, has been recorded again indicating the absence of recharging boundary.

Evaluation of the data by the Jacob's recovery method indicates that a transmissivity (T) of 14.73 m^2/d and a corresponding hydraulic conductivity (K) of 0.5 m/d characterize the aquifer into which the well is placed. The specific capacity after almost 48 hrs of pumping is calculated to be 6.25 $m^3/d/m$ or 0.26 $m^3/hr/m$.

Similar values were obtained for the hydraulic parameters (T and K) from the time-drawdown data of the pumping test (Annex. 12a). Figure 5.6a portrays effect of casing storage (steeper slope) in the earliest part of the test (the first 10 minutes) and hence this part of the curve is not valid in the computation. Otherwise the curve reflects the ideal condition.

The lithological log available for the well is not good enough so as to provide sufficient information in the interpretation of the test data. However, it has been indicated that the aquifer material is represented by weathered acidic rock materials (the type note specified). The K value computed for the well from the pumping test corresponds to the order of magnitude for fractured or weathered volcanic rocks (Kruseman and de Ridder, 1990).



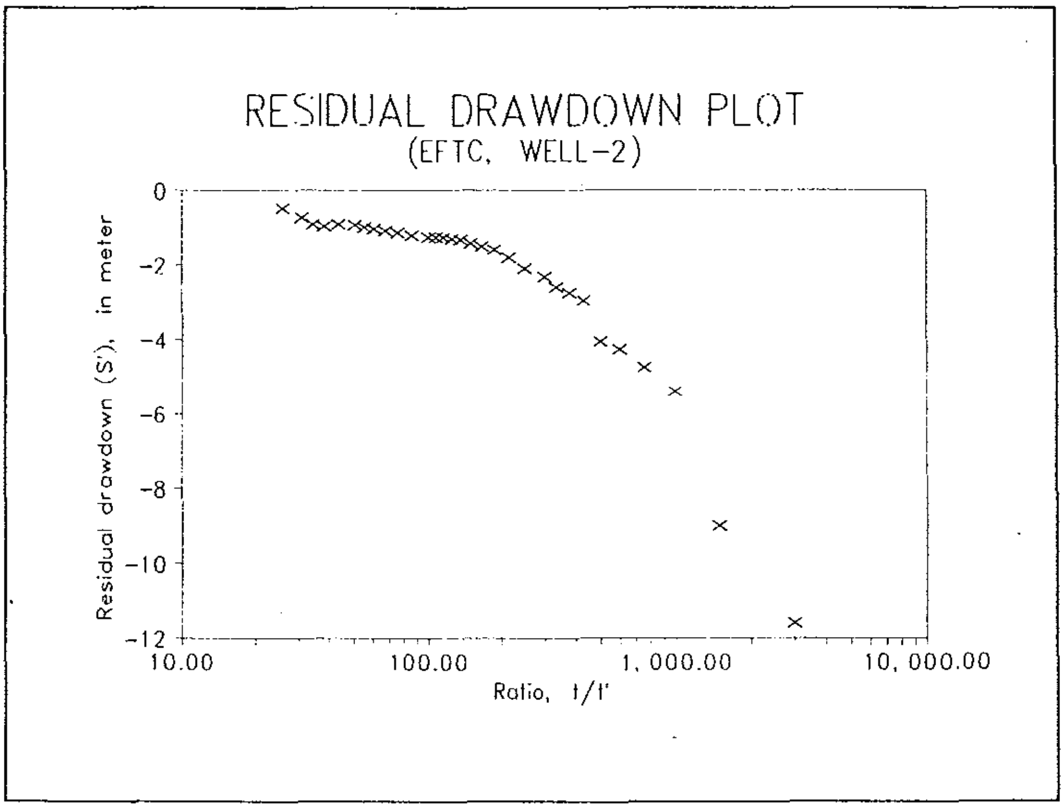


Fig. 5.6 Time-drawdown (a) and Residual drawdown (b) plots of EFTC Well-2

Well-2 (Deka Adi, new well):

It was not possible to get the raw data of the pumping test result for this well. However, according to some studies (Devecon, 1990) which obtained the required data the aquifer constants for the well were determined to be: Transmissivity =49.65 m^2/d and specific capacity = 0.63 $m^3/hr/m$.

From the pumping test results it can be noted that most of the wells in the Melka Hida well field are tapping water from aquifers with good hydraulic characteristics. Transmissivity (T) values for the wells range from 14.73 to 1355.2 m^2/d, and permeability (K) values range from 0.50 to 78.56 m/d. Specific capacity (Sc) varies from 0.26 to 9.13 $m^3/hr/m$ (Table. 5.2).

Table 5.2. Results of Pumping Test of wells at Nazret.

No.	Location	$T(m^2/d)$	$K(m/d)$	$Sc(m^3/hr/m)$	$\Delta S'(m)^a$	Remark
10	Melka Hida	364.87	21.15	4.03	0.52	25 m away from Awash
11	Melka Hida	474.00	27.50	9.13	0.40	30 m away from Awash
12	Melka Hida	441.23	25.58	(0.76)[11]	0.43	200 m away from Awash
13	Melka Hida	863.41	50.00	5.70	0.22	200 m away from Awash
14	Melka Hida	1355.2	78.50	1.50	0.14	25 m away from Awash
2	EFTC COMP.	14.73	0.50	0.26		
2	Deka Adi	49.65	-	0.63	-	

a Slope of residual drawdown curve

In general almost all the pumping tests performed on the wells at Melka Hida well field indicate good aquifer condition. Effects of recharge were observed, in almost all of the wells, after a certain time of pumping depending on their respective distances from the recharge source and on the transmissivity of the aquifer material. The recharge is

[11] This particularly low value of specific capacity is mainly due to the effect of casing storage during early part of pumping period of the test.

believed to come from the nearby Awash river. Additional recharge, although not significant, is also expected from vertical leakage through overlying aquitards in some cases. While pumping test result for the aquifers in other parts of the area (Deka Adi well north of Nazret and EFTC well) show poor aquifer condition with low transmissivity and permeability values, and low specific capacity. Although, no pumping test data is available, similarly poor aquifer condition is expected for the other wells distributed both within the town and northeast of it.

6. Water Chemistry

6.1. Sampling and Analysis

In assessing groundwater potentiality of an area, investigation of the quality of the groundwater is as equally important as its quantity. This quality is generally attributed to the various chemical, physical, biological and radiological constituents of the water. However, the chemical (and physical) quality of the groundwater in Nazret and its surrounding is referred to herein.

It is widely known that groundwaters contain different salts in solution which are acquired from the surrounding soil and rock materials, liquids and gases with which they may come to contact in the various parts of the hydrologic cycle (Todd, 1980; Quilan and Woolly, 1969). That is, the type and concentration of the various constituents are largely dependent on the environment, movements and source of the groundwater. Thus, the geology of an area plays an important role in this respect.

The commonest chemical constituents which are widely considered when dealing with chemical quality of water in an area include: calcium (Ca^{++}), magnesium (Mg^{++}), sodium (Na^{+}), potassium (K^{+}), fluoride (F^{-}), sulphate (SO_4^{--}), chloride (Cl^{-}), nitrate (NO_3^{-}), bicarbonate (HCO_3^{-}) and carbonate (CO_3^{--}) (usually expressed as ionic concentrations). Other minor constituents are represented by components such as silica (SiO_2) and various cations and anions.

Chemical analyses were carried out, to mainly determine the major cations and anions, on a number of water samples collected by the author from bore wells, hand dug wells and from river Awash on March 7 and 8, 1994. Sampling sites were chosen so as to be as representative as possible of the entire study area. Few additional chemical analyses data available , from other sources, determined about the same season in 1990 have also been utilized.

Chemical analyses were done at the laboratory of WSSA, Central Region, using spectrophotometry and titration methods. In addition to this, field determination of mainly the physical properties of water of the study area such as temperature, odour, colour, etc. have also been done. Digital pH meter was used to determine pH values in the field. Site determination of electrical conductivity could not be done due to equipment failure. The results of the analyses which form the basis for the forth coming discussion are depicted in annex 6 and table 6.5. On site temperature ranging from around 25°C up to 42.5°C (DS_9) has been observed in the groundwaters of the area.

It was not possible to carry out bacteriological tests on the water of the area due to problems related to sampling and analysis.

It should be noted that quality required of a groundwater supply depends on its particular purpose. Thus, various quality criteria for the respective needs have been established by different international organizations and governments. Hence, the quality of the water of the study area has been examined with respect to these criteria to check the suitability of the water for various purposes.

6.2. Geochemical Characteristics

The geochemical characteristics of water of the study area is discussed in different sections below.

6.2.1. pH

The pH value of a solution, generally, represents an inverse measure of hydrogen ion concentration in the solution in terms of common positive numbers ranging from 0 to 14. It is the measure of alkalinity and acidity, and is expressed in terms of hydrogen ion concentration as in the following equation.

$$pH = -\log (H^+) \qquad 6.1$$

Pure water at 25°c, which is characterized by a pH value of 7 is by definition taken as a neutral solution[12]. Hence, if the pH is greater than 7 the solution is alkaline and if less than this value acidic. The pH level in natural waters range from 6 to 8 (Raghunath, 1982).

pH values of the various water samples have been determined using pH meter fitted with two electrodes. The results (Table 6.1) show that a pH value that ranges from 6.9 to 8.2 characterizes the samples. Almost all samples taken from the ground and surface waters in the study area are slightly alkaline. Only one sample (BS_8) is some what on the acid side.

From the results of the analyses, it can be seen that the pH values of all the samples is within the permissible limit for drinking purposes which is 6.5 to 8.5 (WHO, 1984).

The relative amount of carbonate ion, bicarbonate ion, and carbonic acid in natural waters varies with the pH (Mason, 1966). For pH values of less than about 8.2, the water is characterized by high bicarbonate concentration. Accordingly,

[12] pH of 7 implies a hydrogen ion concentration of 10^{-7} mole per litre. If the concentration is greater than that of pure water at the same temperature (25°C), the solution is said to be acidic; if it is lesser alkaline (Mason, 1966).

therefore, one can say that HCO_3^- is the dominant anion in the water of the study area. This is well confirmed by the results of the chemical analyses (Table 6.3).

Table 6.1. pH values of water samples at Nazret

Reference No.	Water point	pH value (25°c)
BS_1	Deka Adi (old well)	7.5
BS_2	EFTC[13] (well-2)	7.0
BS_3	Yilma Deresa (well-2)	7.1
BS_4	Well-7	7.5
BS_5	Well-13	8.0
BS_6	Well-14	8.1
DS_1	Wonji (dug well)	7.6
RS_1	Awash R. (Melka Hida)	8.2
BS_7	Wake Tiyo (bore well)	-
BS_8	Adama Ras Hotel (well-2)	6.9
BS_9	Well-2	7.1
BS_{10}	Well-4	7.2
BS_{11}	Well-11	7.3
BS_{12}	Wonji (village-A)	-
BS_{13}	Wonji (village-C)	-
RS_2	Awash R. (Koka)	7.3
RS_3	Awash R.(Wonji Bridge)	8.0

6.2.2. Electrical Conductivity (Ec) and Total Dissolved Solids (TDS)

Electrical conductivity of water (commonly measured in $\mu S/cm$)[14] is a measure of its ability to conduct electric current, and this depends on the amount of ions in solution. The higher the concentration of these charged ions the higher the conductivity. Though, the Ec is more a measure of the ionic concentration than of the total dissolved solids, which

[13] Ethiopian Freight Transport Corporation

[14] micro siemens per centimetre

includes all solid materials in solution occurring as both ionic and undissociated species, a direct relationship is found between the Ec and the TDS particularly for simple solutions like river water. That is;

$$\text{TDS in ppm} = 0.64 \times \text{Ec in } \mu S/cm \qquad 6.2$$

The TDS can be determined in two ways. One is from direct Ec measurements using the above relation for more dilute solutions (river water) and the other is by adding the amounts of cations and anions together with other undissociated species (commonly SiO_2) found by chemical analyses. The first method is used for the river samples from the study area. While the TDS of the groundwater samples was determined from concentration of constituents. Wide range of TDS value has been found mainly in the groundwater samples (Table 6.2). TDS in these samples ranges from 469.92 mg/l to 1791 mg/l with only two samples having TDS lesser than 735 mg/l. The river samples have relatively much smaller amounts of TDS than the groundwater ones and they contain less than 400 mg/l of TDS. One sample (BS_7) is expected to have particularly very low TDS (values not specified) probably due to low degree of rock-water interaction in the aquifer.

The high TDS values particularly in the southern part of the study area indicates that there is high degree of water-rock interaction in the aquifers. Some contribution might also come from the utilization of fertilizers for the plantation in the Wonji Sugar Estate.

The groundwater of an area can be classified in reference to table 6.3 based on the total dissolved solids content. Based on this table most of the groundwater in the study area fall into Fresh Water category. However, the groundwater from the shallow aquifers around Wonji Sugar Estate has a higher TDS and hence is Brackish.

Table 6.2. Amount of TDS and Ec values of different water samples.

Reference No.	Well location or No.	TDS (mg/l.)	Ec (μS/sec.)
BS_1	Deka Adi (2)	743.41	858.41
BS_2	EFTC (2)	764.77	920.00
BS_3	Yilma Deresa (2)	-	710.00
BS_4	Well-7	944.00	1040.00
BS_5	Well-13	469.92	530.00
BS_6	Well-14	623.66	765.00
DS_1	Wonji (dug well)	1253.53	1274.35
RS_1	Awash R.	401.34	491.20
BS_7	Wake Tiyo	-	-
BS_8	Adama Ras Hotel (2)	(805.16)	807.18
BS_9	Well-2	735.40	-
BS_{10}	Well-4	750.35	-
BS_{11}	Well-11	846.10	-
BS_{12}	Wonji (village-A)	1791.00	1793.00
BS_{13}	Wonji (village-C)	1221.00	1223.00
RS_2	Awash R. (Koka)	261.97	409.33
RS_3	Awash R.	306.72	497.25

Table 6.3. Simple groundwater classification based on the amount of TDS (after Caroll).

	Total Dissolved Solids, mg/l
Fresh Water	0 to 1,000
Brackish Water	1000 to 10,000
Saline Water	10,000 to 100,000
Brine	More than 100,000

6.2.3. Hardness

The cause of hardness in water is the presence of mainly calcium and magnesium together with other less abundant ions (alkaline earth metals and heavy metals). Since, most of the hardness is caused by calcium and magnesium, it has become customary to express the hardness (H) in terms of the concentration of these two ions. Thus, the total hardness can be calculated, using the relation below, from the values found for Ca^{++} and Mg^{++} (in mg/l) in the chemical analyses.

$$H = 2.497\ Ca^{++} + 4.115\ Mg^{++} \qquad 6.3$$

According to Sawyer and McCarty (1967), the degree of hardness in water can be classified as depicted in table 6.4

Wide range of hardness is shown by the different water samples of the study area. Based on the above table, the water in the area ranges mainly from Moderately hard to Hard (the later being predominant). One particular sample, however, shows large hardness value (577 mg/l) and is classified as Very Hard water.

Table 6.4. Hardness classification of water (after Sawyer and McCarty)

Hardness, mg/l as $CaCo_3$	Water Class
0 - 75	Soft
75 - 150	Moderately Hard
150 - 300	Hard
over 300	Very Hard

6.2.4 Major Cations and Anions

The concentration of the different major ions in the water of the study area expressed in chemical equivalence (meq/l)[15] and in weight-volume (mg/l) is depicted in table 6.5 and annex 6 respectively. The concentration of silica (SiO_2), which is

[15] melliequivalent per litre

the main undissociated species in the water samples, is also given in mg/l.

The relative ionic (cations and anions) concentration of the chemical analyses based on the average values among the groundwater and river samples is presented as a circular diagram in figure 6.1. The sectors within the circular diagram show the fractions of the different ions expressed in milliequivalents per litre.

The dominant cations are sodium (Na^+) and calcium (Ca^{++}) throughout. The former is relatively more dominant in all the groundwater samples and the later is more dominant in the river water samples. The range of variation for sodium is from 2.59 to 12.62 meq/l for groundwater samples and from 1.12 to 1.77 meq/l for samples from the river Awash. While calcium varies between 0.08 and 8.48 meq/l for the groundwater samples and shows limited variation between 1.36 and 3.19 meq/l in the river samples. Minor cations are magnesium (Mg^{++}) and potassium (K^+). The concentration for both is always less than 1 meq/l except for two samples (Bs_{11} and Bs_{12}) with a bit larger values for Mg^{++}. The concentration of Na^{++} is greater than that of K^+ all in all.

The abundance of Na^+ and Ca^{++} in the water samples could be attributed to the fact that between pH values of 5 and 8 the element oxides Na_2O and CaO (in reference to concentration of alumina) are almost totally removed as the composition of silicate rocks changes on weathering. While a significant decrease and a minor decrease occur in the MgO and K_2O respectively (Brownlow, 1979). This causes relative enrichment of the two cations (Na^+ and Ca^{++}) in the water of the study area where silicate rocks are abundant. The same explanation could hold true for the dominance of Na^+ over K^+ together with the fact that potassium minerals have relatively higher resistance to weathering than sodium minerals and potassium combines more easily with other products of weathering, while sodium remains in solution. Other sources of calcium in particular are related to the mafic rocks such as basalt.

The primary anion in the water of the study area is bicarbonate (HCO_3^-) with concentrations ranging from 3.78 to 13.54 meq/l for the groundwater samples and from 2.3 to 4.3 for samples from the river.

Because of the pH in the water of the area which is largely between 6.9 and 8, almost all dissolved CO_2 is expected to be in the form of HCO_3^- and negligible amount or none is believed to occur as CO_3^{--} as is also reported in the chemical analyses. Therefore, the alkalinity as represented by CO_3^{--} ion content is zero. Hence, the hardness in the water of the area is mainly due to the cations Ca^{++} and Mg^{++}, and the anion HCO_3^-.

Because bicarbonate or carbonate ion are not believed to be main component of any of the minerals in the host rocks of the study area, the higher concentration of HCO_3 ion in the water of the area could only be bound to the dissolution of water under the presence of mainly atmospheric and also possibly magmatic and organic CO_2.

Other minor anions include; chloride (Cl^-), sulphate (SO_4^{--}), fluoride (F^-) and nitrate (NO_3^-). The first two anions occur almost in the same order. The concentration of chloride ranges between 0.1 and 1.46 meq/l for the groundwater samples and does not exceed 0.4 meq/l for samples from the river. Sulphate varies from 0.02 up to 0.96 meq/l with the exception of one sample (Bs_{12}) which shows high sulphate concentration of 7.02 meq/l. This anomalous concentration could be related to local chemical conditions which most probably involves fumarolic activity. Water samples from Awash River were found to be devoid of this anion. Fluoride ranges from 0.03 up to 0.7 meq/l. Nitrate occurs in amounts which rarely exceed 0.5 meq/l and its concentration in the river samples is negligible or nil.

Table 6.5. Chemical analyses result of water samples. (concentrations in meq/l unless specified)

Ref. No.	Ca	Mg	Na	K	Cl	F	HCO_3	CO_3	SO_4	NO_3	$(SiO_2)^a$	Σcat-Σani
BS_1	2.79	0.33	4.53	0.47	0.24	0.03	7.64	nil	0.02	neg.[b]	95.00	0.01
BS_2	2.39	0.68	5.59	0.47	0.68	0.12	6.80	nil	0.08	-	100.9	1.45
BS_3	3.26	0.92	3.26	0.36	0.33	0.05	6.32	nil	0.27	0.16	-	0.67
BS_4	2.04	0.52	7.74	0.50	1.31	0.27	8.03	nil	0.96	0.18	100.1	0.05
BS_5	2.07	0.43	2.59	0.55	0.57	0.13	3.78	nil	nil	0.60	85.40	0.56
BS_6	3.05	0.44	2.92	0.28	0.23	0.12	6.08	nil	0.15	0.06	86.70	0.05
DS_1	0.94	0.17	12.6	0.67	0.88	0.53	11.96	nil	0.71	-	107.0	0.32
RS_1	3.19	0.25	1.12	0.19	0.23	0.07	4.30	nil	nil	neg.	-	0.15
BS_7	0.08	0.09	0.12	0.01	0.01	0.01	0.08	-	0.01	neg.	-	0.19
BS_8	2.18	0.64	5.44	0.33	0.10	0.70	7.96	-	0.33	-	109.1	-0.50
BS_9	3.36	0.53	3.70	0.66	1.46	0.18	6.40	nil	0.26	0.59	80.00	-0.64
BS_{10}	3.21	0.80	3.70	0.68	0.60	0.25	6.80	nil	0.50	0.24	85.00	0.00
BS_{11}	3.36	1.12	4.73	0.34	0.80	0.26	8.00	nil	0.31	0.21	94.00	-0.03
BS_{12}	8.48	3.04	10.0	0.51	1.21	0.12	13.54	-	7.02	-	126.0	0.15
BS_{13}	0.75	0.41	11.7	0.38	1.33	0.53	11.06	-	0.85	-	143.0	-0.48
RS_2	1.36	0.24	1.26	0.14	0.40	0.06	2.60	nil	nil	neg.	23.50	-0.06
RS_3	1.36	0.24	1.77	0.17	0.40	0.10	2.30	nil	nil	nil	30.00	0.74
Minimum	0.08	0.09	0.12	0.01	0.01	0.01	0.08	nil	nil	nil	23.50	-
Maximum	8.48	3.04	12.6	0.68	1.46	0.53	13.5	nil	7.02	neg.	143.0	-
Average	2.58	0.64	5.64	0.39	0.63	0.21	6.63	nil	0.67	0.15	90.41	-

a in milligram per litre b negligible

From the occurrence almost in similar amount of chloride in the water samples taken both from the deep groundwater sources and shallow aquifers, one can say that the chloride concentration could not only be related to surface processes or coming from rain but also inherited from the host rock lithology. It is also known that various forms of chlorine and fluorine are commonly associated with volcanic and fumarolic gases. The source of the sulphate is believed to be related to the oxidation of sulphides, in the presence of O_2, which have their sources associated to the volcanic and geothermal activity in the area. The source of fluoride is again believed to be mainly associated to the fumarolic activity. The primary source of nitrate is taken to be from N_2 of the atmosphere and other minor sources could be attributed to animal excrement (mainly around Wonji, owing to the widely exercised cattle fattening activity) and utilization of fertilizers (again mainly around Wonji) for the irrigation plantation scheme in the area.

Silica, which represents the primary undissociated species in the water of the area, occurs in concentrations ranging from 80 to 143 mg/l in the groundwater samples. The samples from the river shows less than 30 mg/l of silica. When weathering occurs to the silicate minerals of mainly the igneous rocks in an area, silica is added in solution to the groundwater resulting in a higher silicate concentration. Hence the silica concentration in the water of the study area depends, among other factors, on the ease and extent of breakdown of silica minerals in the host rocks. Despite the relation that might commonly occur between silica concentration and pH, samples from the study area do not show any apparent relationship between the two (Fig. 6.2)

Higher concentration of silica, in the study area, is particularly observed for samples taken from the hand dug well and other shallow wells around Wonji Sugar Estate. This high concentration of silica is most likely a result of increased temperature gradient related to the geothermal activity in this place which increases solubility of silica and favours intense water-host rock reaction.

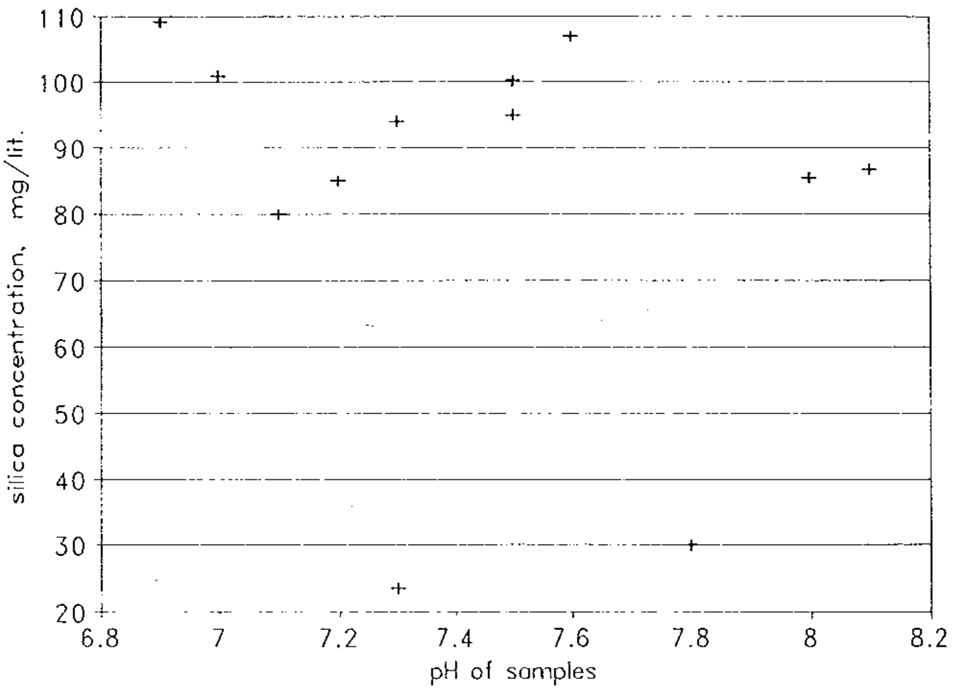
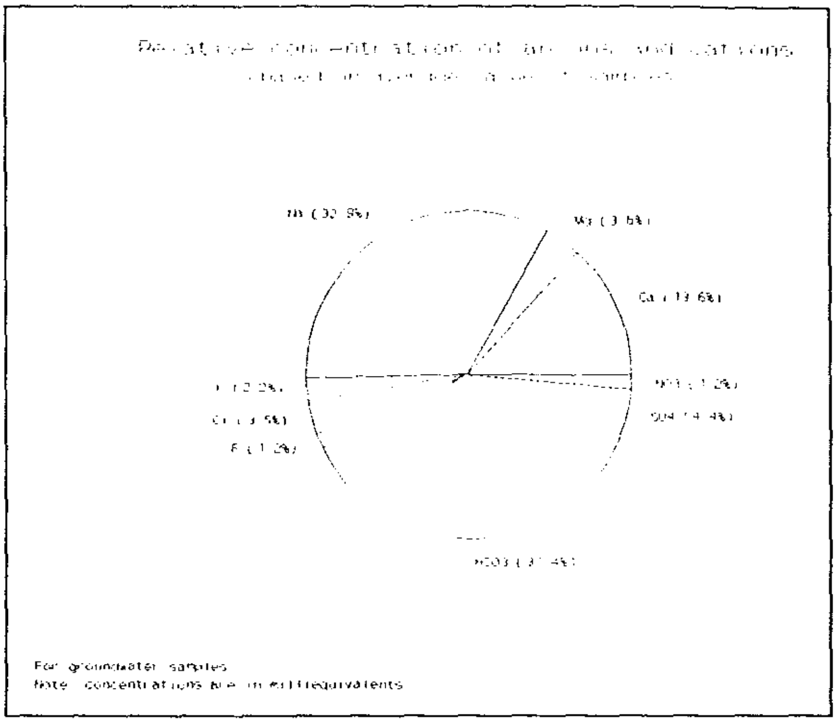


Fig. 6.2. Graph of silica concentration versus pH of samples.

No systematic variation is apparent in the aerial distribution of the dominant cations in the study area. Nor there is any well defined trends in the variation of the other constituents observed. Nevertheless, the dominant anion which is bicarbonate, generally shows slightly higher concentrations for the water samples representing the shallow aquifers around Wonji and from some of the wells in Melka Hida well field as compared to waters from larger depth obtained from other parts of the study area. The TDS also behaves likewise.

Variations in the concentration of the dominant ions occur even among adjacently located wells (as particularly is observed for the wells at Melka Hida) implying a rapid variation in lithology and lesser interconnectivity of the aquifers. Other causes of this variation could be connected to the effects of locally absorbed gases of magmatic origin contributing dissolved mineral products mainly to the groundwater. This could be evidenced by the presence of mineralized thermal springs in few places in the study area.

The other important thing to mention here is that the shallow aquifers at Melka Hida well field are believed to be largely supplied by recharge water from the nearby Awash River. This can have a marked effect on the quality of the groundwater in this place. Besides, these and the other shallow aquifers around Wonji Sugar Estate can also have their chemical quality modified by recharge from rain water owing to the shallow depth and relatively higher permeability of the rocks (sediments) in these places. While limited opportunity for recharge and movement of water is expected for the much deeper aquifers throughout the most part of the study area and hence it is concluded that no significant seasonal or periodical changes in chemical constituents is expected for the waters from these aquifers. But, for the waters from the shallow aquifers (especially for those bordering the river) seasonal and periodical changes in chemical quality is speculated.



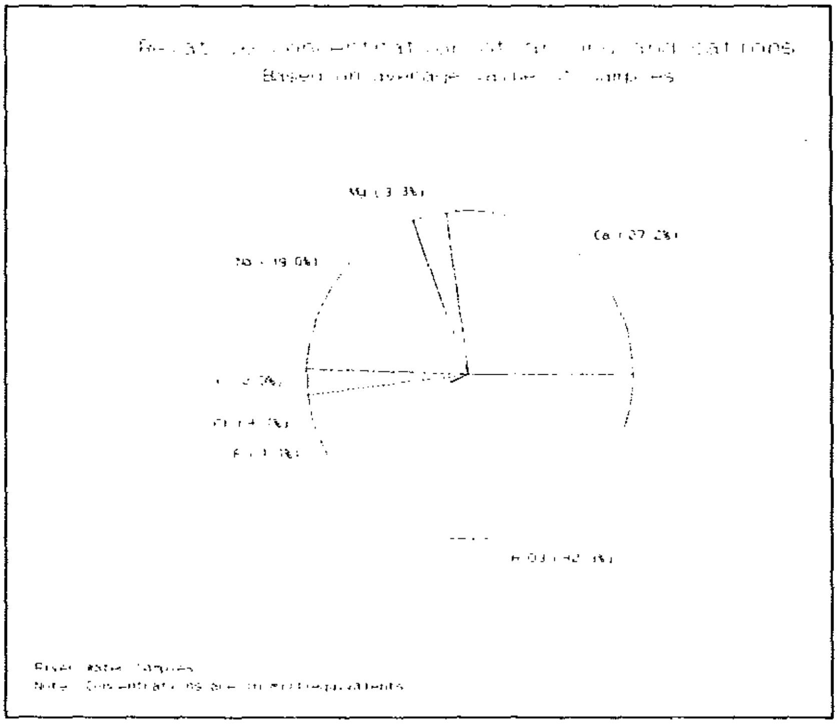


Fig. 6.1. Relative concentration of cations and anions in the groundwater (above) and river water (below) samples.

The common Piper diagram (Fig. 6.3) has been used for comparing the water quality analyses and classifying water types. Accordingly, the main cations (Na^+ + K^+, Ca^{++} and Mg^{++}) and anions (HCO_3^-, Cl^-, SO_4^{--}, and NO_3^-) have been plotted (Fig. 6.3). For each water sample the amount of cations (expressed as percentages of total cations in meq/l) and anions (expressed as percentages of total anions in meq/l) are plotted on the left and right triangles respectively as two points in the figure. These two points are then projected into the central main diagram as a single point that is related to the total ionic distribution for the individual samples.

In spite of the wide range in composition of the samples, waters of the study area can be generally classified as bicarbonate types varying from mostly Na-bicarbonate to Ca-bicarbonate ones. A single sample (Bs_4) has been observed to be characterized by a relatively higher SO_4^{--} and Cl^- content (greater than 35% on the piper diagram) representing a mixed type water. Since sulphides and chlorides are not common component of minerals of host rocks such as that of the study area, the increased sulphide and chloride in this and other samples is expected to be associated to the high temperature geothermal activity.

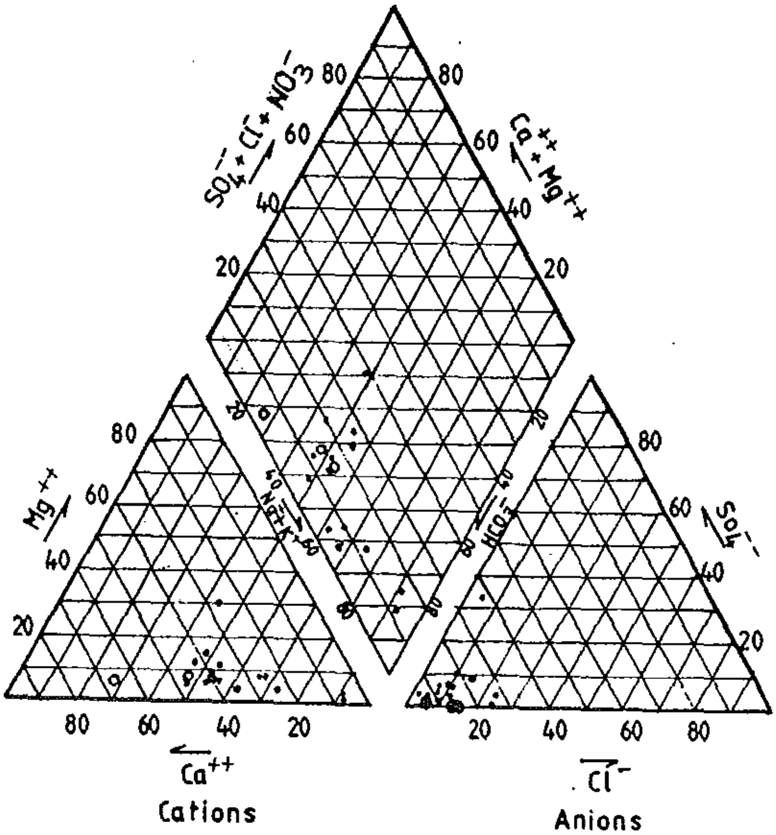


Fig.6.3. Trilinear Diagram Representing Analyses of Water at Nazret.

6.3. Water Quality

As previously mentioned, quality required of ground and surface water of an area depends on its particular purpose. The suitability of the water of the study area for various purposes has been checked in comparison with international standards of acceptable quality limits for drinking, agricultural (irrigation) and industrial uses.

6.3.1. Water quality criteria for drinking purposes

The suitability for drinking purpose of water of the study area has been checked in reference to the standard for drinking water quality set by WHO (1984).

According to table 6.7, the pH in the water of the area which ranges between 6.9 and 8.2 is within the acceptable limit of 6.5 to 8.5. Similarly, the total dissolved solids in most of the samples is below the maximum standard limit of 1000 mg/l. However, some samples especially from around Wonji have higher TDS values.

In many of the samples, on sight temperature has usually been observed to be more than 25 C (Table. 6.7) implying a lesser potability of the water in this respect.

Although the concentration for many of the various constituents of the water samples from the study area meets the quality requirements for drinking purposes (Table 7.6), the water generally has some quality problems in terms of some of the constituents. The main problem is the fluoride content. The fluoride concentration in many of the samples is simply too high above the maximum acceptable limit of 1.5 mg/l. It reaches as large as 10.2 mg/l particularly for samples taken from around Wonji Sugar Estate.

The high fluoride concentration is also evidenced by the occurrence of dental fluorosis among the residents of the area. Fikre Mariam (1986), in his study on the prevalence of dental fluorosis among high school students (9^{th} to 11^{th} grade) in Nazret, indicated that about 68.6% of the students borne and brought up in Nazret are affected by teeth mottling. It is also believed that the people residing particularly around Wonji are exposed to more serious effects of high fluoride content in the water like pronounced mottling or disfiguration of teeth and skeletal fluorosis.

The major source of the fluoride is believed to be bound to the fumarolic or geothermal activity in the area, although some of the fluoride might be attributed to the composition of the volcanic rocks.

Table 6.7. Standards for drinking water quality (WHO, 1984)

Parameters	Recommended Max. or Min-Max
Test and odour	inoffensive
Colour	15 TCU[16]
Turbidity	5 NTU[17]
Temperature	12 - 25 °C
pH	6.5 - 8.5
Conductivity	400 - 1250 μS/cm
Hardness, as $CaCO_3$	500 mg/l
Calcium	10 - 200 mg/l
Magnesium	5 - 50 mg/l
Sodium	<20 - 100 mg/l
Potassium	10 - 12 mg/l
Sulphate	400 mg/l
Chloride	5 - 250 mg/l
Nitrate	45 mg/l
Fluoride	0.7 - 1.5 mg/l
Iron	0.3 mg/l
Manganese	0.1 mg/l

6.3.2. Quality Criteria for Irrigation Purposes

Besides the wide variety of soil types, climatic conditions, irrigation practices, etc., the irrigation water properties are of paramount importance in modifying plant growth and yield. These properties have their effects both on the plant and the soil which supports it. Irrigation water modify the soil by causing changes in the soil structure, permeability, aeration, etc..

Since irrigation waters are ground and surface waters that are used to irrigate farmland, the suitability of water of an area for this purpose should be examined. Total salinity and

[16] Nephelometric turbidity unit

[17] True colour unit

the specific ion content of these waters are the primary properties in dealing with irrigation quality. However, specific limits of permissible salt concentrations are not stated for there is a wide variation in salinity tolerance among plants. Nevertheless, various suitability classes based on some properties of the irrigation water have been developed to examine the quality for this purpose of water of an area. Most classification systems include electrical conductivity (expressing total dissolved solids), sodium content,and boron concentration.

In evaluating the quality of water for irrigation the concentration of sodium is an important factor. This is because of the effect of sodium on the physical properties of the soil resulting in reduced permeability. The sodium concentration in irrigation waters is commonly expressed in terms of percent sodium (% Na), defined by

$$\%Na = \frac{(Na+K)\,100}{Ca+Mg+Na+K} \qquad 6.4$$

where concentrations are in meq/l.

The values of percent sodium and conductivity of the water samples are listed in table 6.8.

Table 6.8. Percent sodium (% Na), Sodium adsorption ratio (SAR) and conductivity of the water samples.

Ref. No.	Well location or No.	Ec (μS/sec.)	% Na	SAR	Water Class
BS_1	Deka Adi (2)	858.41	46.17	3.62	Permissible
BS_2	EFTC (2)	920.00	66.37	4.51	Doubtful
BS_3	Yilma Deresa (2)	710.00	46.41	2.25	Permissible
BS_4	Well-7	1040.00	76.30	6.65	Doubtful
BS_5	Well-13	530.00	55.67	2.31	Permissible
BS_6	Well-14	765.00	47.83	2.21	Permissible
DS_1	Wonji (dug well)	1274.35	92.29	17.05	Unsuitable
RS_1	Awash R.	491.20	27.58	0.85	Good
BS_7	Wake Tiyo	-	43.30	0.41	Permissible
BS_8	Etegie Hotel (2)	807.18	67.17	4.57	Doubtful
BS_9	Well-2	-	52.58	2.66	Permissible
BS_{10}	Well-4	-	52.21	2.61	Permissible
BS_{11}	Well-11	-	53.09	3.15	Permissible
BS_{12}	Wonji (village-A)	1793.00	47.73	4.17	Permissible
BS_{13}	Wonji (village-C)	1223.00	91.27	15.45	Unsuitable
RS_2	Awash R. (Koka)	409.33	46.67	1.99	Permissible
RS_3	Awash R.	497.25	54.80	1.99	Permissible

Note: a) Water classes based on table 6.9.
b) Underlined values determine water class.

Table 6.9 shows classification of irrigation water on the basis of percent sodium (soluble-sodium percent) and electrical conductivity. According to this table , most of the water samples of the study area have good or permissible quality for irrigation. However, three samples have doubtful quality and tow samples from the shallow aquifers at Wonji have unsuitable quality for irrigation.

Table 6.9. Classification of water for irrigation (after Wilcox)

Water Class	Percent Sodium	Specific Conductance (in $\mu S/cm$)
Excellent	< 20	< 250
Good	20 - 40	250 - 750
Permissible	40 - 60	750 - 2000
Doubtful	60 - 80	2000 - 3000
Unsuitable	> 80	> 3000

When a soil is in exchange with an irrigation water, its percentage of exchangeable sodium will closely be related to the calculated sodium adsorption ratio (SAR) of the water (Ciacco, 1971), defined by

$$SAR=\frac{Na}{\sqrt{\frac{(Ca+Mg)}{2}}} \qquad 6.5$$

where the ionic concentrations in the irrigation water are expressed in meq/l. Calculation of the SAR provides an indication of sodium hazard of the water on the soils and crops. That is , the higher the SAR, the greater is the sodium hazard. This value together with the conductivity are also used to classify irrigation waters based on the salinity hazard. A graphic classification (Fig.3.4) by the US Salinity laboratory is employed to plot some of the water samples of the study area. According to this figure most of the plotted groundwater samples are characterized by medium to high salinity hazard and low sodium hazard. One sample (hand dug well from Wonji) have both very high salinity and sodium hazard. Samples from the river show medium salinity and low sodium hazards.

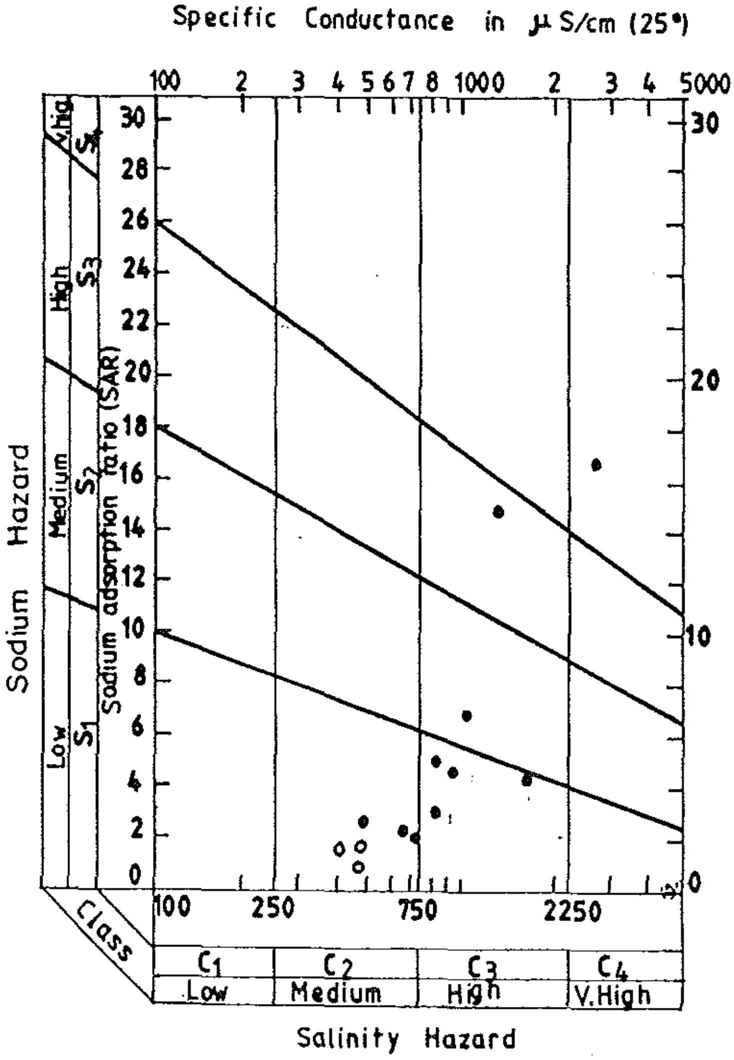


Fig. 6.4. Diagram for Classification of Irrigation water (after Richards) at Nazret.

6.3.3. Quality Criteria for Industry

Water quality requirements for industrial use depends on the type of the industry. Hence, various recommended standards have been set for different industries (Table 6.10 and 6.11). Salinity, hardness and silica content are the main parameters commonly considered while dealing with the quality of water for industrial purposes.

Different industries which include food processing, confectionery, paper and pulp, sugar, diary and others are known to exist in the study area or in its closest vicinity. The water of the area has been examined in comparison to the recommended quality criteria set for these and other industries.

The water quality needed for food processing in general is similar to that of for drinking water. Besides potability, water used for this purpose must meet the requirements depicted in table 6.10.

According to table 6.10, most of the groundwater samples have bicarbonate, silica and fluoride contents which are generally above the recommended limits implying doubtful quality of the groundwater of the area for food processing purposes. While all the river samples fit the standards required.

For the other selected industries listed in table 6.11 the river water samples meet most quality requirements for the respective industrial uses. Except for industrial uses like diary,tanning and sugar production the groundwater samples indicate a generally lower quality when compared to the quality limits for many of the parameters shown in table 6.11. The concentration of mainly Fe and Mn was not utilized in the evaluation for it has not be determined in the chemical analyses. The fluoride concentration, which in particular is much higher than the recommended limit, in almost all the water samples as concerning to textile industry needs to be noted.

Table 6.10. Water quality criteria for food processing, food canning and freezing industries (after the American Water Works Ass.)

Parameters	Acceptable Limits
Turbidity	1 - 10
Colour	5 - 10
Taste and Odour	Inoffensive
Dissolved solids	850 mg/l
Total hardness as $CaCO_3$	10 - 250 mg/l
Total alkalinity as $CaCO_3$	30 - 250 mg/l
Total solids	1000 mg/l
pH	> 7.5
Sodium (Na^+)	300 mg/l
Potassium (K^+)	-
Magnesium (Mg^{++})	40 mg/l
Calcium (Ca^{++})	80 mg/l
Iron (Fe^{++})	0.2 mg/l
Manganese (Mn^{++})	0.2 mg/l
Chloride (Cl^-)	300 mg/l
Fluoride (F^-)	1.0 mg/l
Nitrite (NO_2^-)	-
Nitrate (NO_3^-)	20 mg/l
Bicarbonate (HCO_3^-)	300 mg/l
Carbonate (CO_3^{--})	-
Sulphate (SO_4^{--})	-
Silica (SiO_2)	50 mg/l

Table 6.11. Ranges in recommended limiting concentrations of waters for selected industries (mg/lit) (after Amer. Water Works Ass.).

Use	Turbidity units	Colour units	TDS	H_T as $CaCO_3$	pH	Cl	SO4	Fe	Mn	F	Other requirements
Paper and pulp, fine	10	5	200	100[a]	–	–	–	0.1	0.05	–	soluble SiO_2, 20; free CO_2, 10; residual Cl_2,2
Paper, kraft, bleached	40	25	300	100	–	200	–	0.2	0.1	–	Soluble SiO_2, 50; free CO_2, 10
Sugar	–	–	low	low	–	20	20	0.1	–	–	Ca, 20; Mg, 10; HCO_3,100
Confectionery	–	–	50–100	soft	>7	–	–	0.2	0.2	–	Potable
Tanning	20	10–100	–	50–500	6–8	–	–	0.1–0.2	0.1–0.2	–	low bicarbonate hardness
Textile	0.3–25	0–70	–	0–50	–	100	100		0.1–1	0.05–1	COD 8; metals none; Ca, 10; Mg, 5; HCO_3,200
Rayon manufac.	0.3	–	–	55	7.8–8.3	–	–	0	0	–	–
Diary	–	None	500[b]	180	–	30	60	0.1–0.3	0.03–0.1		Potable; NO_3 -N, 5.5; NO_2 -N, 0

a calcium hardness

b total solids

7. Conclusion and Recommendation

Conclusion

The study area is characterized by a generally warm climate with mean annual temperature and mean annual rainfall of 21°C and 822 mm respectively. It is classified as semi-humid to semi-arid environment. There are only small diurnal and seasonal variations in temperature. While the hydrologic parameters rainfall, evapotranspiration and runoff show significant seasonal variations. Rainfall shows a significant seasonal variation that almost more than 70% of the rain in the area occurs in the four months of June , July, August and September. The rainfall pattern in the area does not generally show significant variation through time. But, in recent years, the mean monthly values for the month of May seems to show a general increase. However, the annual totals showed almost no change for the last few decades.

Due to the high daily temperature and low relative humidity, the amount of potential evapotranspiration is higher than that of the rainfall for the most part of the year except in the three rainy months of July, August and September. Also, it exceeds the actual evapotranspiration except in these three months.

Runoff in the study area occurs only during rain events mainly at times of large storms and Hurton overland flow is the dominant producer of the storm runoff. Runoff leaves the area through more than one pathways. A weighted runoff coefficient of 0.30 to 0.40 has generally been assigned to characterize the study area.

The main cause of the flooding problem of Nazret town is high concentration in short time of rains and the topographic

position of the town. To these can also be added the lack of properly developed sewerage system in the town.

Infiltration is generally low over the study area and it is believed that there is no or limited immediate groundwater response to the rainfall regime in most part of the area except in the alluvial and other aquifers which are bordering Awash river and also in the shallow aquifer zone around Wonji.

Water balance calculation over a small sub-catchment (named Nazret sub-catchment) in the centre of the study area indicates that about 20% of the annual rainfall in the sub-catchment is available for runoff and about 49% of it is lost through direct evapotranspiration. The remaining 30% is accounted for infiltration to the ground representing the amount of water available both to meet the field capacity of the soil and the amount that joins the groundwater. This relation among the hydrologic parameters could be extrapolated over the entire study area to give a general idea.

The aquifers of the area can be broadly classified into two as: a) nonindurated sediments and fragmental or brecciated volcanic deposits having their permeabilities attributable to the primary porosities; and b) dense or massive volcanic rocks which are characterized by permeabilities associated to fractures, joints, faults, zones affected by weathering and/or interbeds. The former are more important than the later in the study area. Specifically the most important aquifers for the groundwater of the area are a) loose pyroclastic deposits: scoriaceous basalts and ciders, pumice falls, unwelded tuffs (when composed of coarse and uniformly sized materials) and volcanic sands b) coarse grained sediments: gravels and sands and lastly c) fractured and/or weathered volcanics: aphanitic and vesicular basaltic flows and ignimbrites. The major faults that have incised the different lithologies in the area serve not only as important conduits for groundwater movement and recharge but also as barrier boundaries of aquifers in some places.

The groundwater occurs under unconfined conditions in the shallow aquifers in the southern part of the area and within confined or semi-confined conditions mainly in the deeper aquifer zone and also sometimes in the shallow aquifer zone. Clays, ashes and loams together with some flows form the confining layers.

From the groundwater contour it can be seen that the general groundwater flow is mainly in the south direction towards Awash river from the deeper aquifer zone. From the shallow aquifer zone groundwater flows again mainly towards Awash river in locally different directions.

From the analyses of the available pumping test data, transmissivity (T) of the aquifers found in the area ranges from 14.73 to 1355.2 m^2/d. And the hydraulic conductivity (K) ranges from 0.50 to 78.50 m/d. No less than 364.87 m^2 and 21.15 m/d have been observed for the T and K of the aquifers at Melka Hida well field. The aquifers found other than in the southern part of the area are generally characterized by much lower permeabilities (reaching 0.50 m/d). The specific capacity of the aquifers has also been found to vary from 0.26 to 9.13 m^3/hr/m.

Analyses of pumping test data of the wells at Mulka Hida well field indicate effects of recharge that most probably comes from the nearby Awash river. The recharge effects reach the wells at times related to their respective distances from the river and depending on the transmissivities of the aquifer materials into which the wells are placed.

Although the water samples in the area show a wide range in composition, high concentration of bicarbonate together with sodium and calcium are apparent all in all. Since bicarbonate ion is not normally a component of the minerals in the different lithologies of the area, the most probable source appears to be the dissolution of water under the presence of mainly atmospheric and possibly magmatic and organic CO_2. The sodium and calcium have their sources mainly related to the dissolution of the minerals of the host rocks.

The groundwater of the area has some quality problem for drinking purpose. The major problem is its fluoride content which in most cases is well above the recommended limit of 1.5 mg/l. Dental fluorosis which is caused by high concentration of fluoride is evident among many of the residents of the area. The fluoride concentration is higher in the southern part, particularly around Wonji, than the rest of the study area. The cause for this increased concentration could be related to the fumarolic activity. The river water from Awash has much lower fluoride concentration which is below or sometimes very slightly higher than the acceptable limit.

The waters of the study area have generally good or permissible quality for irrigation. However, water from some wells have been observed to be hazardous for plant growth.

Concerning industrial quality requirements, the groundwaters of the area are of low quality for food processing industry. Nevertheless, the waters are found to have acceptable quality for other industries like tanning, sugar production, and possibly for others depending on the respective requirements of each type of industry.

Except to the southern part, large part of the study area is characterized by limited groundwater potential not only because of low permeability and specific capacity of the aquifers but also due to the large depth to groundwater which makes exploitation costly. However, there is a possibility to find locally good aquifers which may be formed by buried valleys, depressions along buried faults, or even by fractured and/or weathered zones at depth. On the other hand, the southern part of the area is of great potential and hence, the study area as a whole can generally be considered as having abundant groundwater resources. Nevertheless, these resources are not believed to be sufficient enough to support future demands of the town of Nazret and its surroundings.

In terms of surface water resources, the water from Awash river (found 9 km south of Nazret) could conjunctively used with the groundwater to sufficiently satisfy future water demands. This will also help to improve the quality of water supply through the mixing of the water from the two sources owing to the better quality of the river water.

Recommendation

The following recommendations are forwarded based on the hydrogeological observations made in the study area.

It is necessary to upgrade the class-3 meteorological station at Nazret into a class-1 station which records rainfall (amount and intensity), temperature, relative humidity, wind speed, radiation and evaporation to facilitate future hydrological and hydrogeological studies in the area.

In order to alleviate the existing grievous water problem of the peasant population in the surroundings of Nazret town, the following solutions are recommended. a) Although the aquifers in the vicinity of many of the peasant villages are not believed to be productive enough to get water in significant amount, the placement of even low production wells for the peasant villages is justifiable due to the extent of the existing water problem. Hence, a well drilling program preceded by simple electrical resistivity surveys is necessary. The surveys will help to locate locally important aquifer zones and to estimate their thickness. Hand pumps could be installed to the wells in places where electricity has not reached. b) Despite the high rate of evaporation , it is possible yet to site temporary surface water storage places or artificial ponds which could store water at least for some time after the rain period has passed. The water from these artificial ponds could be used mainly for cattle watering and possibly for small scale irrigation. The abundance of rills, gullies and other water ways together with low permeabilities of the surfacial soil and sediments increases the applicability of this practice.

The exploitation of groundwater from Melka Hida well field should be monitored and development of additional wells, if need be, should be supported by additional studies in order to avoid overdrafting of aquifers and other effects like aquifer collapse.

Additional more detailed and specific study concerning the amount and condition of recharge from Awash river to the bordering aquifers is recommended.

Since the aquifers at Melka Hida well field and other potential places are believed to be in hydraulic continuity with Awash river, the quality of the groundwater in the wells is influenced by the water from the river. Therefore, the river water quality should be checked periodically by taking samples along the course of the river in the area and its vicinity. This could be done by the local WSSA office.

To prevent immediate contamination of the groundwater particularly in the shallow aquifer zone by various liquid and solid wastes, possible pollution sources like cesspools, septic tanks, cesspits, etc. must be properly located and constructed. A system to properly dump and treat the animal excrement produced by the feedlots at Wonji Kuriftu and Wonji Gefersa villages should be found as soon as possible.

Quality of the groundwater in the area should be given proper attention before new industries are established and any water source should be checked with respect to the quality requirements for each concerned industries.

Nazret town is assumed to have a projected population of about 280,000 in the year 2010. Assuming a per capita water demand of 60 l/c/d, about 16,800 m^3/d of water is required to meet the domestic demand by then. According to Devecon (1990), the public demand in the town was estimated to be about 25% of the domestic demand for the year 1990. This proportion is assumed to remain so at least up to the year 2010. This will come out to be 4,200 m^3/d of water. As to the industrial consumption, assuming it to be about 10% of the domestic demand, about 1,680 m^3/d of water is required in the year 2010. It is believed that irrigation cultivation will only be intensified in places bordering Awash River and, therefore, the irrigation consumption is assumed to be negligible as concerning the town of Nazret. On the other hand, it is assumed that the surrounding peasant villages, at least for the most part, will have their own water sources by the year 2010 through the development of wells in representative places. Therefore, the total daily water requirement of the town in the year 2010 is estimated to be about 22,680 m^3/d.

The infiltration rate in the Nazret sub-catchment was previously determined to be about 19.29×10^6 m^3 per year, which is 52,849 m^3/d. Nevertheless, owing to the low permeability of rocks and loose deposits occupying the sub-catchment and also to the very large depth to groundwater level in it, only very limited proportion of this infiltrated water is believed to join the groundwater reservoir(s). Hence, roughly about 20% of this amount of water is expected to reach the groundwater. This is about 10,569.8 m^3/d and represents the amount of available water in the Nazret sub-catchment. However, the daily water demand of the town for the year 2010 is estimated to be 22,680 m^3/d. The remaining 12,110.2 m^3/d of water, therefore, should come from sources outside of the sub-catchment. These sources include the Melka Hida well field and the river Awash.

Conjunctive use of groundwater and surface water from Awash river is probably the only solution to sufficiently support future water supply of Nazret town and its surrounding. Hence, optimal use of the groundwater in the area at first and then development of surface water exploitation scheme is recommended sequentially.

ANNEXES

Annex 1a. Rainfall data of Nazret.

Year	J	F	M	A	M	J	J	A	S	O	N	D
1953	0.0	X	80.1	X	X	X	X	X	X	X	0.0	41.3
1954	X	X	0.0	0.0	0.0	80	92.5	239	134	40.5	0.0	X
1955	X	X	X	26	38	42.5	234	150	180	40.5	0.0	X
1956	0.0	0.0	5	78	X	40	138	X	X	0.0	X	X
1957	X	X	X	18	19	96	285	199	X	X	X	0.0
1958	0.0	0.0	153	90	X	62	223.4	193	153	8.5	X	X
1959	0.0	58.8	0.0	0.0	0.0	17	132	191	54	3	0.0	0.0
1960	0.0	0.0	0.0	23	66	27	136	54	60	0.0	0.0	X
1961	X	X	X	X	X	X	X	X	X	X	X	X
1962	X	X	X	X	X	X	X	X	X	X	X	X
1963	X	X	X	X	X	X	X	X	X	X	X	X
1964	X	X	X	X	X	X	X	X	X	X	X	27.8
1965	18.1	0.0	15.9	29.8	0.0	121.7	103.2	187.9	44.8	47.5	11.3	0.0
1966	X	86.2	34.7	X	44.5	111.3	X	209.6	116.4	12.4	0.7	0.0
1967	0.0	0.0	65.6	37.8	59.2	91.5	X	X	X	X	X	0.0
1968	X	39.4	45	50.6	3.5	113.1	X	X	X	X	X	X
1970	51.1	27.9	81.1	28.4	18.4	11.5	155.7	305.7	112.1	4.4	0.0	0.0
1971	1.8	0.0	x	x	x	x	192.5	325.8	147.7	1.0	10.2	33.8
1972	1.3	10.5	96.2	86.3	28.0	130.3	273.8	249.3	85.7	6.5	0.0	0.0
1973	0.0	0.0	0.0	0.1	94.2	30.3	125.8	300.2	107.7	78.4	0.0	0.0
1974	0.6	7.3	100.2	0.0	77.3	118.5	180.8	161.7	171.0	1.5	0.0	0.0
1975	1.9	8.5	1.1	101.2	42.0	202.3	469.5	168.5	90.7	x	0.0	x
1976	0.0	x	67.5	64.6	x	48.2	190.0	212.2	108.2	0.2	30.6	7.0
1977	58.2	10.8	58.6	133.7	67.6	139.8	226.2	172.0	83.5	163.0	63.7	0.0
1978	3.2	99.4	2.7	16.3	15.1	59.1	92.2	199.3	82.3	68.3	x	5.5
1979	114.3	20.6	60.9	8.1	127.4	115.6	92.4	128.6	21.8	17.4	x	x
1980	x	x	x	x	x	x	x	x	120.7	39.4	4.3	0.0
1981	0.0	40.7	166.7	57.5	x	2.9	246.3	308.9	137.9	4.7	0.0	0.0
1982	8.8	41.6	34.9	29.7	79.1	31.7	127.4	259.8	47.6	104.5	31.3	10.9
1983	x	43.4	33.8	79.3	188.0	24.7	214.4	221.3	72.4	14.3	0.0	0.0
1984	0.0	0.0	4.3	0.4	178.1	84.6	202.7	148.3	66.9	0.0	0.0	19.8
1985	3.0	x	23.1	183.4	67.3	8.0	405.4	327.1	169.0	0.0	0.0	0.0
1986	0.0	96.5	41.0	6.2	54.4	152.4	263.3	95.0	20.4	0.0	0.0	0.0
1987	0.0	11.2	80.2	81.1	259.6	0.0	161.6	243.4	30.8	0.0	0.0	0.0
1988	34.0	31.3	6.8	50.9	9.4	53.3	155.4	171.4	186.9	52.9	0.0	0.0
1989	0.0	29.9	21.7	95.4	0.0	54.7	182.5	251.2	80.3	5.7	0.0	3.5
1990	0.7	169.0	83.0	114.7	13.3	12.0	337.8	187.9	153.7	10.8	0.0	0.0
1991	0.0	x	84.2	13.5	22.3	74.4	322.0	232.8	89.0	13.1	x	1.7

Annex 1b. Average Daily Tempereture at Nazret

Year	J	F	M	A	M	J	J	A	S	O	N	D
1953	18.6	-	-	-	-	-	-	-	-	-	20.1	18.9
1954	-	-	22.3	-	22.7	22.8	19.6	20.1	22.2	-	-	-
1955	-	-	-	-	22.6	20.5	20.8	-	-	-	-	-
1956	-	-	-	24.3	-	-	17.7	-	-	-	-	-
1957	-	-	-	21.0	-	-	-	-	-	-	-	-
1958	-	-	-	-	-	-	-	-	-	-	-	-
1959	-	-	-	22.1	22.9	23.3	20.4	19.8	20.6	20.0	19.1	18.3
1960	19.2	21.0	22.0	21.8	23.3	22.5	20.5	-	20.4	-	19.1	-
1961	-	-	-	-	-	-	-	-	-	-	-	-
1962	-	-	-	-	-	-	-	-	-	-	-	-
1963	-	-	-	-	-	-	-	-	-	-	-	-
1964	-	-	-	-	-	-	-	-	-	-	-	-
1965	17.5	19.1	20.2	20.2	19.8	22.5	20.8	19.9	20.1	19.8	14.4	16.5
1966	-	17.1	20.1	-	23.0	21.6	-	20.3	20.0	19.1	18.1	17.6
1967	17.3	20.4	21.9	-	21.8	20.2	-	-	-	-	-	-
1968	-	-	-	-	18.8	18.5	-	-	-	-	-	-
1969	-	-	-	-	23.5	23.9	20.5	19.6	21.6	20.2	19.5	18.3
1970	20.1	21.2	21.3	23.2	24.6	24.5	21.3	20.0	20.9	20.1	17.8	17.5
1971	18.8	19.9	-	-	-	-	20.3	20.0	21.0	20.1	18.8	17.6
1972	19.2	20.3	21.6	22.7	22.8	23.2	20.5	20.6	20.9	20.2	20.0	20.2
1973	19.9	21.6	23.6	25.0	24.0	23.8	21.5	20.4	21.1	20.1	19.3	17.2
1974	19.9	21.4	21.4	22.4	23.0	22.3	20.5	21.0	20.7	19.8	17.8	18.5
1975	19.2	21.2	23.2	22.7	23.6	22.4	19.6	19.6	20.6	-	18.5	-
1976	19.2	-	22.0	22.1	-	23.4	20.6	20.5	21.3	21.0	19.6	19.6
1977	20.5	19.4	22.2	20.1	22.7	22.8	20.5	20.9	21.3	21.3	18.4	18.6
1978	19.3	20.6	22.3	23.8	25.0	23.9	20.9	21.0	21.5	20.3	-	19.8
1979	19.9	20.6	22.0	23.5	23.1	23.1	20.8	20.9	21.0	19.9	-	-
1980	-	-	-	-	-	-	-	-	21.7	20.6	20.3	18.7
1981	20.9	21.7	22.2	21.4	-	25.5	22.0	20.9	20.5	19.8	19.4	18.8
1982	21.1	21.9	23.2	23.3	23.3	24.7	21.7	20.4	21.3	18.8	19.6	19.6
1983	-	21.8	23.7	23.0	23.6	23.7	22.3	20.7	22.1	20.6	19.7	19.2
1984	-	-	-	-	-	-	-	-	-	-	-	-
1985	20.5	-	23.5	22.6	23.3	29.9	21.7	20.2	21.5	19.9	19.6	20.1
1986	20.6	23.0	21.5	23.1	24.6	22.9	21.6	21.3	23.3	19.5	19.8	23.0
1987	18.6	23.2	23.2	22.0	22.3	24.1	22.2	21.6	22.4	21.5	20.2	19.4
1988	21.3	24.0	22.5	22.9	24.0	24.0	18.1	20.8	21.3	18.6	16.4	17.8
1989	19.1	19.9	22.3	20.6	24.4	22.6	18.4	19.5	20.8	19.4	19.3	20.9

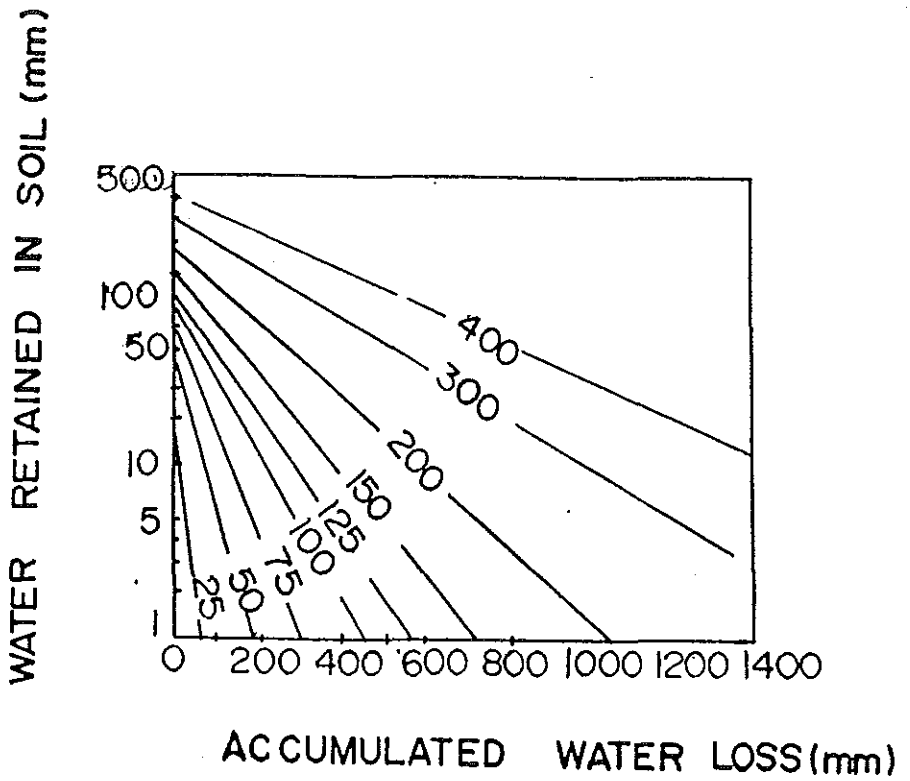
Annex 2. Latitude factor for Thornthwaite evapotranspiration calculation (Leopold and Dune).

Latitude	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
60N	0.54	0.67	0.97	1.19	1.33	1.56	1.55	1.33	1.07	0.84	0.58	0.48
50N	0.71	0.84	0.98	1.14	1.28	1.36	1.33	1.21	1.06	0.90	0.76	0.68
40N	0.80	0.89	0.99	1.10	1.20	1.25	1.23	1.15	1.04	0.93	0.83	0.78
30N	0.87	0.93	1.00	1.07	1.14	1.17	1.16	1.11	1.03	0.96	0.89	0.85
20N	0.92	0.96	1.00	1.05	1.09	1.11	1.10	1.07	1.02	0.98	0.93	0.91
10N	0.97	0.98	1.00	1.03	1.05	1.06	1.05	1.04	1.02	0.99	0.97	0.96
0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
10S	1.05	1.04	1.02	0.99	0.97	0.96	0.97	0.98	1.00	1.03	1.05	1.06
20S	1.10	1.07	1.02	0.98	0.93	0.91	0.92	0.96	1.00	1.05	1.09	1.11
30S	1.16	1.11	1.03	0.96	0.89	0.85	0.87	0.93	1.00	1.07	1.14	1.17
40S	1.23	1.15	1.04	0.93	0.83	0.78	0.80	0.89	0.99	1.10	1.20	1.25
50S	1.33	1.19	1.05	0.89	0.75	0.68	0.70	0.82	0.97	1.13	1.27	1.36

Annex 3. Available water capacities for combinations of soil texture and vegetation.

Vegetation	Soil texture	Avail. water Capacity (% Vol.)	Rooting Depth(m)	Avail. water cap. of root zone(mm)
Shallow rooted crops	Fine sand	10%	0.50	50
(spinach, peas, beans	Fine sandy loam	15%	0.50	75
beets, carrots, etc.)	Silt loam	20%	0.62	125
	Clay loam	25%	0.40	100
	Clay	30%	0.25	75
Moderatly deep rooted	Fine sand	10%	0.75	75
crops (corn, cereals,	Fine sandy loam	15%	1.00	150
cotton, tobacco)	Silt loam	20%	1.00	200
	Clay loam	25%	0.80	200
	Clay	30%	0.50	150
Deep rooted crops	Fine sand	10%	1.00	100
(alfalfa, pasture	Fine sandy loam	15%	1.00	150
grass, shrubs)	Silt loam	20%	1.25	250
	Clay loam	25%	1.00	250
	Clay	30%	0.67	200
Orchards	Fine sand	10%	1.50	150
	Fine sandy loam	15%	1.67	250
	Silt loam	20%	1.50	300
	Clay loam	25%	1.00	250
	Clay	30%	0.67	200
Mature forest	Fine sand	10%	2.50	250
	Fine sandy loam	15%	2.00	300
	Silt loam	20%	2.00	400
	Clay loam	25%	1.60	400
	Clay	30%	1.17	350

Annex 4 SOIL MOISTURE



(After Leopold B)

Annex 5. Runoff Coefficient (K) over different land types (after Sharma).

Type of catchment	Value of (K)
Rocky and impermeable	0.80 to 1.00
Slightly Permeable, bare	0.60 to 0.80
Slightly permeable, cultivated or covered by vegetation	0.40 to 0.60
Cultivated absorbent soil	0.30 to 0.40
Sandy absorbent soil	0.20 to 0.30
Heavy forest	0.10 to 0.20

Annex 6. Result of Chemical Analyses (mg/l)

Sample Ref.	Cation				Anion					
No.	Ca	Mg	Na	K	HCO_3	Cl	F	SO_4	NO_3	CO_3^{2}
BS_1	55.88	4.00	104.2	18.31	466.0	14.85	0.61	0.02	neg.[a]	nil
BS_2	47.99	8.30	128.4	18.30	418.8	24.25	2.37	4.00	nil	nil
BS_3	65.33	11.18	74.94	14.08	385.6	11.70	1.00	12.97	9.92	nil
BS_4	40.84	6.30	177.9	19.70	492.2	46.25	5.20	46.30	11.21	nil
BS_5	41.57	5.27	59.50	21.40	230.4	20.18	2.53	nil	3.36	nil
BS_6	61.18	5.40	67.20	11.10	371.0	8.25	2.33	7.00	3.50	nil
DS_1	18.78	6.10	290.0	26.10	729.5	31.35	10.02	34.00	-	nil
RS_1	63.94	3.00	25.42	7.33	262.3	8.25	1.30	nil	neg.	neg.
BS_7	1.60	1.08	2.74	0.23	4.80	0.51	0.11	0.33	neg.	-
BS_8	43.69	7.78	125.0	13.00	485.6	3.68	1.32	16.03	-	-
BS_9	67.30	6.40	85.00	25.70	390.4	28.4	3.40	12.30	36.5	nil
BS_{10}	64.40	9.70	85.00	26.40	414.8	21.30	4.85	23.90	15.00	nil
BS_{11}	67.30	13.60	108.8	13.20	488.0	28.40	5.00	14.80	13.00	nil
BS_{12}	170.0	37.00	230.0	20.00	826.0	43.00	2.00	337.0	-	-
BS_{13}	15.00	5.00	270.0	15.00	675.0	47.00	10.0	41.00	-	-
RS_2	27.30	2.90	28.90	5.60	158.6	14.20	1.17	nil	nil	nil
RS_3	27.30	2.90	40.80	6.60	183.0	14.20	1.92	nil	neg.	nil

a negligible

Annex 7a. Pumping test data of Well-10 at Melka Hida, Nazret.

Location: Melka Hida, Nazret
Well No.: 10
Static Water Level: 11.20 m (from top of casing)
Well Depth: 44.98 m
Well Size: 6" PVC casing
Perforated Length: 17.25 m
Discharge: 12 l/sec.
Pumping Date: 03/09/80 EC

Time	Water Level (m)	Progress Time (min)	Drawdown (m)
8:15	11.20	0	0
:16	18.05	1	6.85
:17	18.72	2	7.52
:18	19.08	3	7.88
:19	19.30	4	8.10
:20	19.40	5	8.20
:21	19.51	6	8.31
:22	19.65	7	8.45
:23	19.72	8	8.52
:24	19.78	9	8.58
:25	19.82	10	8.62
:27	19.90	12	8.70
:29	19.95	14	8.75
:31	20.00	16	8.80
:33	20.04	18	8.84
:35	20.07	20	8.87
:37	20.10	22	8.90
:39	20.13	24	8.93
:41	20.16	26	8.96
:43	20.18	28	8.98
:45	20.19	30	8.99
:50	20.22	35	9.02
:55	20.24	40	9.04
9:00	20.26	45	9.06
:05	20.28	50	9.08
:10	20.30	55	9.10
:15	20.32	60	9.12
:25	20.35	70	9.15
:35	20.38	80	9.18

Continued:

9:45	20.42	90	9.22
:55	20.45	100	9.25
10:15	20.48	120	9.28
:35	20.52	140	9.32
:55	20.58	160	9.38
11:15	20.61	180	9.41
:30	20.66	195	9.46
12:00	20.70	225	9.50
:30	20.74	255	9.54
1:00	20.82	285	9.62
:30	20.88	315	9.68
2:00	20.96	345	9.70
3:00	20.92	405	9.72
4:00	20.95	465	9.75
5:00	21.02	525	9.82
6:00	21.04	585	9.84
7:00	21.14	645	9.94
8:00	21.16	705	9.96
9:00	21.20	765	10.00
10:00	21.24	825	10.04
11:00	21.28	885	10.08
12:00	21.33	945	10.13
1:00	21.36	1005	10.16
2:00	21.40	1065	10.20
3:00	21.43	1125	10.23
4:00	21.43	1185	10.23
5:00	21.43	1245	10.23
6:00	21.44	1305	10.24
7:00	21.44	1365	10.24
8:00	21.44	1425	10.24
9:00	21.50	1485	10.30
10:00	21.50	1545	10.30
11:00	21.54	1605	10.34
12:00	21.61	1665	10.41
1:00	21.62	1725	10.42
2:00	21.63	1785	10.43
3:00	21.65	1845	10.45
4:00	21.69	1905	10.49
5:00	21.69	1965	10.49
6:00	21.72	2025	10.52
7:00	21.74	2085	10.54
8:00	21.76	2145	10.56

Continued:

9:00	21.79	2205	10.59
10:00	21.82	2265	10.62
11:00	21.82	2325	10.62
12:00	21.88	2385	10.68
1:00	21.88	2445	10.68
2:00	21.92	2505	10.72
3:00	21.92	2565	10.72
4:00	21.92	2625	10.72
5:00	21.92	2685	10.72
6:00	21.92	2745	10.72
7:00	21.92	2805	10.72
8:00	21.92	2865	10.72

Annex 7b. Recovery test data of Well-11 at Melka Hida, Nazret.

Discharge Rate:12 l/s
Discharge Time: 2865 minute
Recovery Date: 05/9/80 EC

Time	Water Level (m)	Recovery (m)	Residual Drawdown (m)	Time Since Pump Started (t) (min)	Time Since Pump Stopped (t') (min)	Ratio (t/t')
8:01	14.5[illegible]	7.42	3.30	2866	1	2866.00
:02	13.8[illegible]	8.07	2.65	2867	2	1433.50
:03	13.64	8.28	2.44	2868	3	956.00
:04	13.54	8.38	2.34	2869	4	717.25
:05	13.47	8.45	2.27	2870	5	574.00
:06	13.41	8.51	2.21	2871	6	478.50
:07	13.37	8.55	2.17	2872	7	410.28
:08	13.36	8.56	2.16	2873	8	359.12
:09	13.34	8.58	2.14	2874	9	319.33
:10	13.32	8.60	2.12	2875	10	287.50
:12	13.29	8.63	2.09	2877	12	239.75
:14	13.26	8.66	2.06	2879	14	205.64
:16	13.23	8.69	2.03	2881	16	180.06
:18	13.21	8.71	2.01	2883	18	160.16
:20	13.20	8.72	2.00	2885	20	144.25
:22	13.19	8.73	1.99	2887	22	131.22
:24	13.17	8.75	1.97	2889	24	120.37
:26	13.15	8.77	1.95	2891	26	111.19
:28	13.14	8.78	1.94	2893	28	103.32
:30	13.13	8.79	1.93	2895	30	96.50
:35	13.10	8.82	1.90	2900	35	82.85
:40	13.07	8.85	1.87	2905	40	72.62
:50	13.01	8.91	1.81	2915	50	58.30
9:00	12.99	8.93	1.79	2925	60	48.75
:10	12.94	8.98	1.74	2935	70	41.93
:20	12.91	9.01	1.71	2945	80	36.81
:30	12.88	9.04	1.68	2955	90	32.83
:40	12.86	9.06	1.66	2965	100	29.65
10:00	12.79	9.13	1.59	2985	120	24.87
:20	12.74	9.18	1.54	3005	140	21.46
:40	12.70	9.22	1.50	3025	160	18.90
11:00	12.65	9.27	1.45	3045	180	16.91
:20	12.59	9.33	1.39	3065	200	15.32

Continued:

:42	15.42	4.18	102
12:02	15.44	4.20	122
:22	15.45	4.21	142
:42	15.49	4.25	162
1:02	15.53	4.29	182
:32	15.55	4.31	212
2:02	15.56	4.32	242
:32	15.58	4.34	272
3:02	15.58	4.34	302
4:00	15.58	4.34	360
5:00	15.62	4.38	420
6:00	15.64	4.40	480
7:00	15.67	4.43	540
8:00	15.68	4.44	600
9:00	15.70	4.46	660
10:00	15.72	4.48	720
11:00	15.74	4.50	780
12:00	15.76	4.52	840
1:00	15.77	4.53	900
2:00	15.77	4.53	960
3:00	15.80	4.56	1020
4:00	15.80	4.56	1080
5:00	15.81	4.57	1140
6:00	15.81	4.57	1200
7:00	15.81	4.57	1260
8:00	15.83	4.59	1320
9:00	15.83	4.59	1380
10:00	15.84	4.60	1440
11:00	15.86	4.62	1500
12:00	15.89	4.65	1560
1:00	15.91	4.67	1620
2:00	15.92	4.68	1680
3:00	15.93	4.69	1740
4:00	15.94	4.70	1800
5:00	15.95	4.71	1860
6:00	15.95	4.71	1920
7:00	15.95	4.71	1980
8:00	15.96	4.72	2040
9:00	15.97	4.73	2100

Annex 8b. Recovery test data of well-11 at Melka Hida, Nazret.

Discharge Rate: 12 l/s
Discharge Time: 2100 minutes
Recovery Date: 22/08/80 EC

Time	Water Level (m)	Recovery (m)	Residual Drawdown (m)	Time Since Pump Started (t)(min)	Time Since Pump Stopped (t')(min)	Ratio (t/t')
9:01	14.27	1.70	3.03	2101	1	2101.00
:02	13.90	2.07	2.66	2102	2	1051.00
:03	13.72	2.25	2.48	2103	3	701.00
:04	13.59	2.38	2.35	2104	4	526.00
:05	13.47	2.50	2.23	2105	5	421.00
:06	13.38	2.59	2.14	2106	6	351.00
:07	13.30	2.67	2.06	2107	7	301.00
:08	13.22	2.75	1.98	2108	8	263.50
:09	13.14	2.83	1.90	2109	9	234.33
:10	13.08	2.89	1.84	2110	10	211.00
:12	13.01	2.96	1.77	2112	12	176.00
:14	12.96	3.01	1.72	2114	14	151.00
:16	12.92	3.05	1.68	2116	16	132.25
:18	12.89	3.08	1.65	2118	18	117.66
:20	12.86	3.11	1.62	2120	20	106.00
:22	12.83	3.14	1.59	2122	22	96.45
:24	12.80	3.17	1.56	2124	24	88.50
:26	12.78	3.19	1.54	2126	26	81.77
:28	12.76	3.21	1.52	2128	28	76.00
:30	12.74	3.23	1.50	2130	30	71.00
:35	12.72	3.25	1.48	2135	35	61.00
:40	12.70	3.27	1.46	2140	40	53.50
:45	12.69	3.28	1.45	2145	45	47.66
:50	12.68	3.29	1.44	2150	50	43.00
:55	12.67	3.30	1.43	2155	55	39.18
10:00	12.64	3.33	1.40	2160	60	36.00
:10	12.61	3.36	1.37	2170	70	31.00
:20	12.58	3.39	1.34	2180	80	27.25
:30	12.56	3.41	1.32	2190	90	24.33
:50	12.51	3.46	1.27	2210	110	20.09
11:10	12.48	3.49	1.24	2230	130	17.15
:30	12.46	3.51	1.22	2250	150	15.00

Annex 9a. Pumping test data of Well-12 at Melka Hida, Nazret.

Location: Melka Hida, Nazret
Well No.: 12
Type of pump: Submersible
Static water level: 11.20 m (from top of casing)
Well depth: 42.93 m
Well size: 6" PVC
Perforated length: 17.25 m
Pumping date: 12/08/80 EC
Discharge rate: 12 l/s

Time	Water level (m)	Drawdown (m)	Progress time (min)
12:40	11.20	0	0
:41	26.40	15.20	1
:42	28.20	17.00	2
:43	31.90	20.70	3
:44	32.23	21.03	4
:45	32.25	21.05	5
:46	32.40	21.20	6
:47	32.45	21.25	7
:48	32.48	21.28	8
:49	32.48	21.28	9
:50	32.50	21.30	10
:52	32.51	21.31	12
:54	32.48	21.28	14
:56	32.45	21.25	16
:58	32.45	21.25	18
1:00	32.45	21.25	20
:02	32.47	21.27	22
:04	32.47	21.27	24
:06	32.47	21.27	26
:08	32.47	21.27	28
:10	32.47	21.27	30
:15	32.49	21.29	35
:20	32.50	21.30	40
:25	32.50	21.30	45
:30	32.50	21.30	50
:40	32.52	21.32	60
:50	32.52	21.32	70
2:00	32.53	21.33	80

Continued:

:20	32.53	21.33	100
:40	32.53	21.33	120
3:00	32.53	21.33	140
:30	32.54	21.34	160
4:00	32.54	21.34	190
:30	32.54	21.34	220
5:00	32.57	21.34	250
6:00	32.63	21.43	310
7:00	32.69	21.49	170
8:00	32.71	21.51	430
9:00	32.82	21.62	490
10:00	32.94	21.74	550
11:00	33.17	21.97	610
12:00	33.28	22.08	670
1:00	33.37	22.17	730
2:00	33.52	22.32	790
3:00	33.55	22.35	850
4:00	33.89	22.69	910
5:00	33.92	22.72	970

Annex 9b. Recovery test data of Well-12 at Melka Hida, Nazret.

Discharge rate: 12 l/sec.
Discharge time: 970 minute
Recovery date: 26/08/80 EC

Time	Water Level (m)	Recovery (m)	Residual Drawdown (m)	Time Since Pump Started (t) (min)	Time Since Pump Stopped (t') (min)	Ratio (t/t')
5:01	13.40	20.52	2.20	971	1	971.00
:02	12.95	21.07	1.75	972	2	486.00
:03	12.70	21.22	1.50	973	3	324.33
:04	12.50	21.42	1.30	974	4	243.50
:05	12.30	21.62	1.10	975	5	195.00
:06	12.20	21.72	1.00	976	6	162.66
:07	12.13	21.79	0.93	977	7	139.57
:08	12.05	21.87	0.85	978	8	122.25
:09	11.97	21.95	0.77	979	9	108.77
:10	11.94	21.98	0.74	980	10	98.00
:12	11.87	22.05	0.67	982	12	81.83
:14	11.83	22.09	0.63	984	14	70.28
:16	11.80	22.12	0.60	986	16	61.62
:18	11.77	22.15	0.57	988	18	54.89
:20	11.73	22.19	0.54	990	20	49.50
:22	11.70	22.22	0.50	992	22	45.09
:24	11.68	22.24	0.48	994	24	41.41
:26	11.65	22.27	0.45	996	26	38.30
:28	11.62	22.30	0.42	998	28	35.64
:30	11.60	22.32	0.42	1000	30	33.33
:35	11.56	22.36	0.40	1005	35	28.71
:40	11.54	22.38	0.36	1010	40	25.25
:50	11.51	22.41	0.34	1020	50	20.40
6:00	11.49	22.43	0.29	1030	60	17.16
:10	11.47	22.45	0.27	1040	70	14.85
:30	11.44	22.48	0.24	1060	90	11.77
:50	11.42	22.50	0.22	1080	110	9.81
7:10	11.40	22.52	0.20	1100	130	8.46
:40	11.37	22.55	0.17	1130	160	7.06
8:10	11.35	22.57	0.15	1160	190	6.10
:40	11.32	22.60	0.12	1190	220	5.41
9:10	11.31	22.61	0.11	1220	250	4.88
10:10	11.30	22.62	0.10	1280	310	4.13

Continued:

11:10	11.28	22.64	0.08	1340	370	3.62
12:10	11.28	22.64	0.08	1400	430	3.25

Annex 10a. Pumping test data of Well-13 at Melka Hida, Nazret.

Location: Melka Hida, Nazret
Well No.: 13
Type of pump: Submersible
Static water level: 12.05 (from top of casing)
Well depth: 34.72 m
Well size: 6" PVC
Perforated length: 17.25 m
Pumping date: 29/08/80 EC
Discharge: 12 l/s

Time	Water level (m)	Drawdown (m)	Progress time (min)
10:30	12.05	0	0
:31	13.50	1.45	1
:32	13.56	1.51	2
:33	13.61	1.56	3
:34	13.65	1.60	4
:35	13.68	1.63	5
:36	13.72	1.67	6
:37	13.75	1.70	7
:38	13.78	1.73	8
:39	13.80	1.75	9
:40	13.84	1.79	10
:42	13.88	1.83	12
:44	13.92	1.87	14
;46	14.02	1.97	16
:48	14.06	2.01	18
:50	14.11	2.06	20
:52	14.13	2.08	22
:54	14.15	2.10	24
:56	14.18	2.13	26
11:00	14.19	2.14	30
:05	14.20	2.15	35
:10	14.22	2.17	40
:15	14.24	2.19	45
:20	14.25	2.20	50
:25	14.27	2.22	55
:30	14.30	2.25	60
:35	14.33	2.28	65
:40	14.35	2.30	70

Continued:

:45	14.37	2.32	75
:50	14.38	2.33	80
12:00	14.41	2.36	90
:10	14.44	2.39	100
:20	14.47	2.42	110
:30	14.49	2.44	120
:50	14.53	2.48	140
1:10	14.57	2.52	160
:30	14.59	2.54	180
2:00	14.62	2.57	210
:30	14.65	2.60	240
3:00	14.68	2.63	270
:30	14.69	2.64	300
4:00	14.72	2.67	330
5:00	14.75	2.70	390
6:00	14.78	2.73	450
7:00	14.82	2.77	510
8:00	14.84	2.79	570
9:00	14.87	2.82	630
10:00	14.88	2.83	690
11:00	14.89	2.84	750
12:00	14.90	2.85	810
1:00	14.91	2.86	870
2:00	14.92	2.87	930
3:00	14.93	2.88	990
4:00	14.94	2.89	1050
5:00	14.96	2.91	1110
6:00	14.97	2.92	1170
7:00	14.97	2.92	1230
8:00	14.97	2.92	1290
9:00	14.97	2.92	1350
10:00	14.97	2.92	1410
11:00	14.97	2.92	1470
12:00	14.97	2.92	1530
1:00	14.97	2.92	1590
2:00	14.97	2.92	1650
3:00	14.97	2.92	1710
4:00	14.98	2.93	1770
5:00	14.99	2.94	1830
6:00	15.01	2.96	1890
7:00	15.02	2.97	1950
8:00	15.02	2.97	2010

Continued:

9:00	15.03	2.98	2070
10:00	15.04	2.99	2130
11:00	15.04	2.99	2190
12:00	15.05	3.00	2250
1:00	15.05	3.00	2310
2:00	15.05	3.00	2370
3:00	15.06	3.01	2430
4:00	15.07	3.02	2490
5:00	15.08	3.03	2550
6:00	15.08	3.03	2610
7:00	15.08	3.03	2670
8:00	15.08	3.03	2730
9:00	15.08	3.03	2790
10:00	15.08	3.03	2850

Annex 10b. Recovery data of Well-13 at Melka Hida, Nazret

Discharge rate: 12 l/s
Discharge time: 2850 min
Recovery date: 01/09/80 EC

Time	Water level (m)	Recovery (m)	Residual Drawdown (m)	Time Since Pump Started (m)	Time Since Pump Stopped (m)	Ratio t/t'
10:01	13.25	1.85	1.20	2851	1	2851.00
:02	13.16	1.92	1.11	2852	2	1426.00
:03	13.08	2.00	1.03	2853	3	951.00
:04	13.02	2.06	0.97	2854	4	713.50
:05	12.98	2.10	0.93	2855	5	571.00
:06	12.93	2.15	0.88	2856	6	476.00
:07	12.89	2.19	0.84	2857	7	408.14
:08	12.84	2.24	0.79	2858	8	357.25
:09	12.82	2.26	0.77	2859	9	317.66
:10	12.80	2.28	0.75	2860	10	286.00
:12	12.75	2.33	0.70	2862	12	238.50
:14	12.71	2.37	0.66	2864	14	204.57
:16	12.67	2.41	0.62	2866	16	179.12
:18	12.64	2.44	0.59	2868	18	159.33
:20	12.61	2.47	0.56	2870	20	143.5
:22	12.59	2.49	0.54	2872	22	130.54
:24	12.57	2.51	0.52	2874	24	119.75
:26	12.55	2.53	0.50	2876	26	110.61
:28	12.52	2.56	0.47	2878	28	102.78
:30	12.49	2.59	0.44	2880	30	96.00
:35	12.46	2.62	0.41	2885	35	82.43
:40	12.44	2.64	0.39	2890	40	72.25
:45	12.42	2.66	0.37	2895	45	64.33
:50	12.41	2.67	0.36	2900	50	58.00
:55	12.40	2.68	0.35	2905	55	52.82
11:00	12.39	2.69	0.34	2910	60	48.50
:10	12.37	2.71	0.32	2920	70	41.71
:20	12.35	2.73	0.30	2930	80	36.62
:30	12.34	2.74	0.29	2940	90	32.66
:50	12.32	2.76	0.27	2960	110	26.91
12:10	12.30	2.78	0.25	2980	130	22.92
:30	12.29	2.79	0.24	3000	150	20.00
1:00	12.28	2.80	0.23	3030	180	16.83
:30	12.27	2.81	0.22	3060	210	14.57

Continued:

2:00	12.26	2.82	0.21	3090	240	12.87
:30	12.25	2.83	0.20	3120	270	11.55
3:00	12.25	2.83	0.20	3150	300	10.50
4:00	12.23	2.85	0.18	3210	360	8.91
5:00	12.22	2.86	0.17	3270	420	7.78
6:00	12.21	2.87	0.16	3330	480	6.93
7:00	12.20	2.88	0.15	3390	540	6.27
12:00	12.17	2.91	0.12	3690	840	4.39

Continued:

:20	21.27	10.60	80
:30	21.28	10.61	90
:40	21.28	10.61	100
5:00	21.32	10.65	120
:20	21.36	10.69	140
:40	21.40	10.73	160
6:00	21.44	10.77	180
:20	21.48	10.81	200
:50	21.50	10.83	230
7:20	21.51	10.84	260
:50	21.52	10.85	290
8:50	21.56	10.89	350
9:50	21.58	10.91	410
10:50	21.60	10.93	470
11:50	21.60	10.93	530
12:50	21.63	10.96	590
1:50	21.63	10.96	650
2:50	21.66	10.99	710
3:50	21.70	11.03	770
4:50	21.70	11.03	830
5:50	21.73	11.06	890
6:50	21.75	11.08	950
7:50	21.76	11.09	1010
8:50	21.79	11.12	1070
9:50	21.79	11.12	1130
10:50	21.79	11.12	1190
11:50	21.79	11.12	1250
12:50	21.79	11.12	1310
1:50	21.75	11.07	1370
2:50	21.74	11.06	1430
3:50	21.74	11.06	1490
4:50	21.76	11.09	1550
5:50	21.78	11.11	1610
6:50	21.80	11.13	1670
7:50	21.83	11.16	1730
8:50	21.85	11.18	1790
9:50	21.90	11.23	1850
10:50	21.91	11.24	1910
11:50	21.94	11.27	1970
12:50	21.94	11.27	2030
1:50	21.98	11.31	2090
2:50	21.98	11.31	2150

Continued:

3:50	21.99	11.32	2210
4:50	22.00	11.33	2270
5:50	22.00	11.33	2330
6:50	22.00	11.33	2390
7:50	22.00	11.33	2450
8:50	22.00	11.33	2510
9:50	22.00	11.33	2570
10:50	22.00	11.33	2630
11:50	22.00	11.33	2690
12:50	22.00	11.33	2750
1:50	22.00	11.33	2810
2:50	22.00	11.33	2870

Annex 11a. Recovery test data of Well-14 at Melka Hida, Nazert.

Discharge Rate: 12 l/sec.
Recovery Date: 29/09/80 EC

Time	Water Level (m)	Recovery (m)	Residual Drawdown (m)	Time Since Pump Started (m)	Time Since Pump Stopped (m)	Ratio t/t'
2:50	22.00	0	11.33	2870	0	-
:51	11.80	10.20	1.13	2871	1	2871.00
:52	11.40	10.60	0.73	2872	2	1436.00
:53	11.30	10.70	0.63	2873	3	957.66
:54	11.20	10.80	0.53	2874	4	718.50
:55	11.12	10.88	0.45	2875	5	575.00
:56	11.05	10.95	0.38	2876	6	478.33
:57	11.02	10.98	0.35	2877	7	411.00
:58	11.01	10.99	0.34	2878	8	359.75
:59	10.98	11.02	0.31	2879	9	319.88
3:00	10.96	11.04	0.29	2880	10	288.00
:02	10.94	11.06	0.27	2882	12	240.16
:04	10.90	11.10	0.23	2884	14	206.00
:06	10.88	11.12	0.21	2886	16	180.37
:08	10.87	11.13	0.20	2888	18	160.44
:10	10.86	11.14	0.19	2890	20	144.50
:12	10.84	11.16	0.17	2892	22	131.45
:14	10.82	11.18	0.15	2894	24	120.58
:16	10.81	11.19	0.14	2896	26	111.38
:18	10.80	11.20	0.13	2898	28	103.50
:20	10.79	11.21	0.12	2900	30	96.66
:35	10.78	11.22	0.11	2915	45	64.77
:40	10.77	11.23	0.10	2920	50	58.40
:45	10.76	11.24	0.09	2925	55	53.18
:50	10.75	11.25	0.08	2930	60	48.83
:55	10.74	11.26	0.07	2935	65	45.15
4:00	10.74	11.26	0.07	2940	70	42.00
:10	10.73	11.27	0.06	2950	80	36.87
:20	10.73	11.27	0.06	2960	90	32.88
:30	10.72	11.28	0.05	2970	100	29.70
:50	10.71	11.29	0.04	2990	120	24.91
5:10	10.71	11.29	0.04	3010	140	21.50
:30	10.70	11.30	0.03	3030	170	17.82
6:00	10.69	11.31	0.02	3060	200	15.30

Annex 12a. Pumping test data of EFTC Well-2, Nazret.

Location: EFTC Compound ,Nazret
Well No.: 2
Type of pump: Submersible
Static water level: 162.1 m (from top of casing, 0.87 m a.g.s)
Well depth: 194.5 m
Perforated length: 29.66 m
Pumping date: 29/12/83 to 30/12/83 EC
Discharge : 1.2 l/sec.

Time	Water Level (m)	Drawdown (m)	Progress (t) (min)
9:00	162.10	0	0
:01	169.00	6.90	1
:02	169.75	7.65	2
:03	171.00	8.90	3
:04	171.30	9.20	4
:05	171.85	9.75	5
:06	172.10	10.00	6
:07	172.40	10.30	7
:08	172.75	10.65	8
:09	173.05	10.95	9
:10	173.25	11.15	10
:12	173.70	11.60	12
:14	173.85	11.75	14
:16	174.30	12.20	16
:18	174.45	12.35	18
:20	174.70	12.60	20
:22	174.75	12.65	22
:24	174.82	12.72	24
:26	174.90	12.80	26
:28	174.95	12.85	28
:30	175.00	12.90	30
:35	175.00	12.90	35
:40	175.20	13.10	40
:45	175.35	13.25	45
:50	175.41	13.31	50
:55	175.50	13.40	55
10:00	175.66	13.56	60
:05	175.70	13.60	65
:10	175.76	13.66	70

Continued:

:20	175.80	13.70	80
:30	176.00	13.90	90
:40	176.20	14.10	100
11:00	176.30	14.20	120
:20	176.35	14.25	140
:40	176.40	14.30	160
12:00	176.45	14.35	180
:20	176.50	14.40	200
:50	176.65	14.55	230
1:20	176.70	14.60	260
:50	176.90	14.80	290
2:50	177.00	14.90	350
3:50	177.00	14.90	410
4:50	177.00	14.90	470
5:50	177.00	14.90	530
6:50	177.30	15.20	590
7:50	177.50	15.40	650
8:50	177.80	15.70	710
9:50	177.86	15.76	770
10:50	177.92	15.82	830
11:50	177.98	15.88	890
12:50	178.02	15.92	950
1:50	178.10	16.00	1010
2:50	178.15	16.05	1070
3:50	178.20	16.10	1130
4:50	178.26	16.16	1190
5:50	178.30	16.20	1250
6:50	178.32	16.22	1310
7:50	178.34	16.24	1370
8:50	178.36	16.26	1430
9:50	178.41	16.31	1490
10:50	178.44	16.34	1550
11:50	178.49	16.39	1610
12:50	178.54	16.41	1670
1:50	178.60	16.50	1830
2:50	178.65	16.55	1890
3:50	178.70	16.60	1950
4:50	178.75	16.65	2010
5:50	178.78	16.68	2070
6:50	178.85	16.75	2130
7:50	178.90	16.80	2190
8:50	178.95	16.85	2250

Continued:

9:50	178.98	16.88	2310
10:50	179.00	16.90	2370
11:50	179.05	16.95	2430
12:50	179.08	16.98	2490
1:50	179.12	17.02	2550
2:50	179.17	17.07	2610
3:50	179.21	17.11	2670
4:50	179.25	17.15	2730
5:50	179.31	17.21	2790
6:50	179.34	17.24	2850
7:50	179.36	17.36	2910
9:00	179.38	17.28	2980

Annex 12b. Recovery test data of EFTC Well-2, Nazret.

Location: EFTC Compound, Nazret
Static water level: 162.1 m
Test date: 1/13/83 EC
Discharge rate (before pump stopped): 1.2 l/sec

Time	Water level (m)	Recovery (m)	Residual Drawdown (m)	Time Since Pump Started (t) (min)	Time Since Pump Stopped (t') (min)	Ratio t/t'
9:00	0	0	17.28	2980	0	-
:01	173.70	5.65	11.60	2981	1	2981.00
:02	171.10	8.28	9.00	2982	2	1491.00
:03	167.50	11.88	5.40	2983	3	994.33
:04	166.85	12.53	4.75	2984	4	746.00
:05	166.35	13.03	4.25	2985	5	597.00
:06	166.15	13.23	4.05	2986	6	497.67
:07	166.05	14.33	2.95	2987	7	426.71
:08	164.85	14.53	2.75	2988	8	373.50
:09	164.70	14.68	2.60	2989	9	332.10
:10	164.42	14.96	2.32	2990	10	299.00
:12	164.20	15.18	2.10	2992	12	249.33
:14	163.90	15.48	1.80	2994	14	213.86
:16	163.70	15.68	1.60	2996	16	187.25
:18	163.60	15.78	1.50	2998	18	166.55
:20	163.50	15.88	1.40	3000	20	150.00
:22	163.42	15.96	1.32	3002	22	136.45
:24	163.40	15.98	1.30	3004	24	125.16
:26	163.36	16.02	1.26	3006	26	115.61
:28	163.36	16.02	1.26	3008	28	107.43
:30	163.36	16.02	1.26	3010	30	100.33
:35	163.32	16.05	1.22	3015	35	86.14
:40	163.25	16.13	1.14	3020	40	75.50
:45	163.20	16.18	1.10	3025	45	67.22
:50	163.18	16.20	1.05	3030	50	60.60
:55	163.10	16.28	1.00	3035	55	55.18
10:00	163.05	16.33	0.95	3040	60	50.66
:10	163.00	16.38	0.92	3050	70	43.57
:20	162.94	16.44	0.96	3060	80	38.25
:30	162.90	16.48	0.92	3070	90	34.12
:40	162.85	16.53	0.75	3080	100	30.80
11:00	162.60	16.75	0.50	3100	120	25.83

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