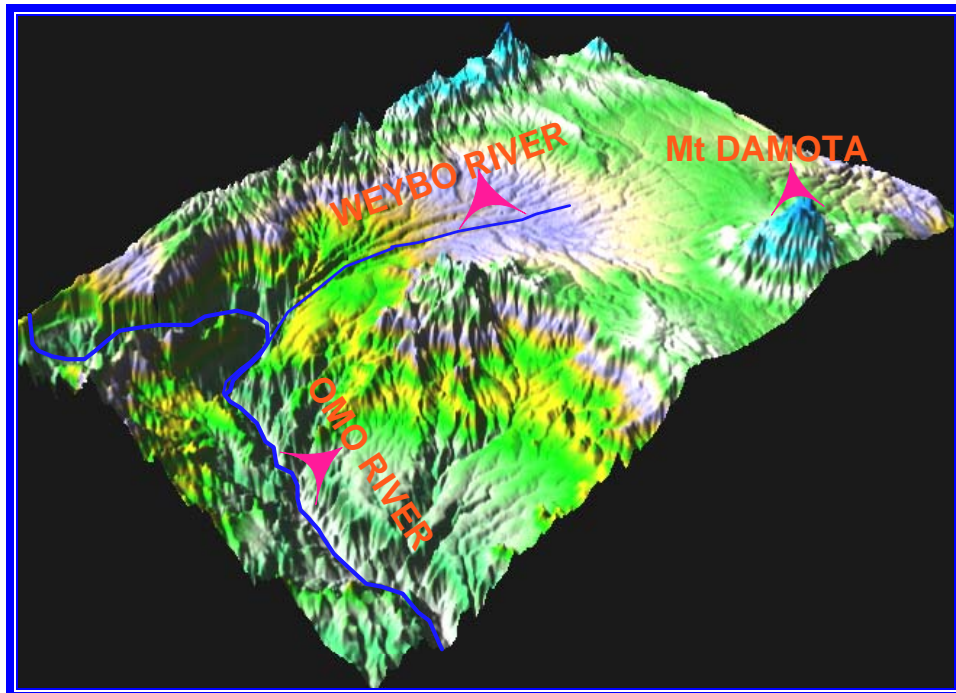




**ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES**

**INTEGRATED WATER RESOURCES POTENTIAL
INVESTIGATION OF THE WEYBO RIVER CATCHMENT
WELAYITA-HADIYA ZONES, SOUTHERN ETHIOPIA**



AYCHLUHIM DEBEBE

JUNE 2006

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WELAYITA-HADIYA ZONES, SOUTHERN ETHIOPIA**

**A THESIS SUBMITTED TO
THE SCHOOL OF GRADUTE STUDIES
ADDIS ABABA UNIVERSITY**

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THE DEGREE MASTERS OF SCIENCE IN
HYDROGEOLOGY**

**BY
AYCHLUHIM DEBEBE**

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Abstract

The Weybo river catchment is located in the southern part of Ethiopia. It is confined by the major Omo-Gibe Basin and situated at the south-west margin of the Main Ethiopian Rift.

The area is dominantly covered by acid volcanics, both pyroclastic flows and falls, of Miocene to Pliocene age.

Integrated approaches are adopted to effect the assessments of water resources potential of the catchment. The different components, controls and/or parameters in each of the methods are estimated, computed or qualitatively described applying different empirical and physical techniques. The different techniques greatly help compare resultant values of some parameters, controls or components. It is this comparison that help generate ideas on the power of workability of that specific technique in the study area.

This new work reveals an overall balance among the components of the water budget. Soil moisture deficits are recorded in months of November through mid March and the remaining 7 months remain in surplus. However, it has been investigated that the ground water recharge is declining in an appreciable rate for a small decrease in precipitation and a moderate increase in surface runoff. The remaining hydrometeorological parameters show a lower to moderate increase for the last 15-20 years.

Ground water potential of the Weybo River catchment is seen to be under the control of fracturing intensity and degree of weathering. Higher hydraulic conductivity zones are mapped at or near fractured regions and their values are decreasing away from the structures. It has also been seen that aquifers that are formed from the deeply weathered ignimbrites, rhyolites and trachytes yield low and possess a lower hydraulic conductivity generally in the order of 0.1-0.5.

The apparent resistivity values do not show a clear contrast between the highly weathered aquifer formations and the fractured ones. Lower and nearly similar values (1-10 Ω -m) are obtained in both regions.

Both graphical and statistical presentations of the physical and chemical parameters of the water samples provide a good deal of information on the characteristics of ground water flow systems, recharging and discharging zones, and aquifer interconnectivity in east and north-east parts of the study area and its neighboring watershed. Piper, Collins, Schoeller, HCA and 2-dimensional surfer plots have been used to facilitate analyses and interpretations of the data.

Chloride-mass-balance technique results an over-estimated rate of recharge in the study area, which is calculated to be 123.5mm/annum. The most likely justifications are cited, and suggestions are also forwarded in a view to bring the method in to effect.

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I am indebted to the South Omo Zone Rural Development Coordination Department and Water Resources Development Office, for allowing me to pursue my postgraduate studies.

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1. Introduction

1.1 Background

Weybo river catchment, the investigated area, hosts both rural and semi-rural communities, with a characteristics of dense settlement, high rate of population growth, extensive and poorly developed farming practices and a large portion of the area is formed from a complex volcanic geology.

All tributaries and the upper reaches of the main Weybo River are characteristically seasonal except in its lower reach and in some of the developed tributaries that drain the northern and north-eastern portions of the catchment.

The catchment is contained within the Omo-Gibe basin, one of the seven major basins of the country, placed in the central (shifted to the east) part of the basin.

In connection with the higher population size, and the complex geo-hydrologic set up of the study area, availing the demanded amount and quality of water in a sustainable manner, for a variety of purposes especially for drinking and domestic uses, live stock watering and agriculture and other development and social activities does require, apart from the requirement of some amount of economic investment, an integrated investigation and evaluation approaches.

Multi-exploratory approaches and methodologies evolve with the advancing sciences and technology, which have been testified on a variety of environmental set-ups for their workability and effectiveness. However, application of the practical exploration techniques in the real world may not always yield reliable results for the fact that the very important parameters that exist on both the surface and sub-surface systems are hard to quantity for quantification procedures are associated with some degrees of uncertainties. Such limitations/uncertainties could be improved through synergizing multi-exploration and evaluation methodologies.

In this research project, it has been tempted to synergize the effects of the methods in hydrology, geology, hydrogeology, hydro-geochemistry and hydro-geophysics to come up with a good degree of confidence with respect to the potentialities of the resource.

Broadly the investigation help understand the current situation and fate of the potentialities of the resource of the study area in particular, and the whole basin, especially the central and upper parts of Omo-Gibe, in general.

1.2 Previous works

Among the works, that addresses the study catchment, Omo-Gibe River Basin Integrated Development Master plan (December 1996, FDRE, Ministry of water resources) is cited. The Natural Resources Surveys and Inventories, which is contained in volume-8 of the master plan, reveal the geology, soil, and water resources of the catchment in a very narrow scale.

Commission of Sustainable Agriculture and Environment Rehabilitation of Southern Region, Study and Design Department (April 1997), carried out a reconnaissance study report for small scale irrigation project in BolosoSore wereda. The evaluation targeted at prioritization of streams for suitability of irrigation structures. Same commission carried out feasibility studies on two rivers draining the catchment, Magera and Weybo. Both the reconnaissance and feasibility studies are not published. None of these reports show the ground water potential of the catchment and do not quantify or qualitatively describe most of the very important hydrologic and hydrogeologic parameters.

The Ethiopian Agricultural Research Organization, National Soil Research Center, Soil Survey and Land Evaluation Section, carried out a research on soils of Areka agricultural research center (July 2003). The study focused on the categorization of the soil types based on field and soil chemistry parameters of the specific area, research center compound, and mapping is done in a scale of 1:5000.

In general, published researches and scientific exercises within the study area could not be found posing a lack in detail and sub-detail information.

1.3 Objectives of the study

General objectives

Quantifying the ground water potential of the catchment and showing the effects of the integrated evaluation methods.

Specific Objectives

- Quantification of the major hydrologic components
- Zonation of permeability ranges within the catchment there by mapping potential zones
- To show the regional and local flow systems of ground water in the catchment
- To produce hydrogeological map of the study area
- To show some of the applications of hydrogeochemical methods on resources potential evaluation
 - ▶ Application of chloride mass balance on recharge estimation and comparing the value with those obtained from other methods
 - ▶ Delineating recharge and discharge zones through analyses of the chemistry of the water.
 - ▶ Delineating the regional, local and intermediate groundwater flow systems through mapping of some of the parameters
 - ▶ Analyses of the hydrochemistry of water samples to show aquifer connectivity of the catchment with adjacent catchments

1.4 Methodology

- Characterization of all the litho-units, geological structures and physiography in connection with the hydrogeology of the study area and adjacent catchments
- Characterization of the hydrological and hydro-geophysical conditions of the catchment and its surroundings
- Characterization of the meteorological elements within and in the surroundings of the catchment
- Characterization of the chemistry of the water from different sources within and adjacent to the catchment
- Applications of remote sensing, geographic information systems, and other computer codes to facilitate analyses, synthesis, and interpretation of the results and make ease of bulk data management.

Specific

Classification of activities in to office and field, and further in to preliminary and feasibility phases of investigation

The office works comprise of –

- ▶ Collection and organization of previous works within and around the study area
- ▶ Plotting all developed water schemes on a 1:50000 topographic maps
- ▶ Thorough interpretation of 1:50000 topographic maps
- ▶ Thorough interpretation of 1:100000 landsat satellite images in a regional scale
- ▶ Interpretation of 3-dimensional global maps at a scale of 1:100000
- ▶ Understanding of the geologic and hydrogeologic set-ups of the catchment and adjacent catchments through observation of borehole logs from well completion reports, water well sitting reports, pumping test reports, irrigation schemes study reports, and water schemes inventory reports

Field activities include-

- ▶ Observations and mapping of outcrops of different lithological units in and around the study area
- ▶ Visual observation of geological structures and interpreted/inferred structures
- ▶ Observations and descriptions of undeveloped water schemes
- ▶ Georeferencing both constructed and undeveloped water sources
- ▶ Collecting water samples for laboratory analyses (temporal series)
- ▶ Measuring in-situ field parameters of water samples
- ▶ Conducting vertical electrical soundings in pre-defined locations
- ▶ Lithological logging of hand dug wells constructed by the local community and organizations
- ▶ Observation of land-cover and land-use practices
- ▶ Identification of perennial and intermittent stream reaches
- ▶ Georeferencing distributions of meteorological and river discharge gauging stations and identification of their classes (types).

2. Brief Description of the study area

2.1 Location, Areal Extent and Accessibility

Weybo river catchment, a tributary of Omo River, draining the Omo-Gibe basin, is located at the South-Western boundary of the Main Ethiopian Rift being situated out of the rift system. It is found in the Southern Nations and Nationalities People's Region of Welaita and partially Hadia zones at a distance 420Km from Addis Ababa and 200Km from the regional town, Awassa.

Hadia, Dawuro and Kembata -Tembaro zones of SNNPR border the catchment from North, West and North-East respectively. The catchment is geographically bounded between 6° 55' 42'' and 7° 10' 28'' N latitude, and 37° 31' 39'' and 37° 46' 40'' E longitude with an areal extent and perimeter of 574Km² and 124Km respectively.

The Addis Ababa – Welaita – Areka, Addis Ababa – Durame – Areka or Addis Ababa – Butajira – Hosaina – Areka partial asphalt and partial all weather roads provide alternative access to the area. Three of the mentioned transport corridors distant 410, 440 and 300Kms from Addis Ababa respectively. An asphalt highway serves the Addis Ababa – Welaita and Addis Ababa – Butajira routes.

The roads within the study area are all weather and have a good networking that enable to access in every direction especially to villages, small towns and almost to all constructed water schemes. The problem in connection with accessibility is that many intermittent streams and some perennial rivers cross the roads. Many local fords made of woods are constructed. Those fords are not durable and safe and could not support heavy vehicles and machineries. In some places, these poorly developed and under maintained wooden fords are built across perennial streams.

Transport of people and goods in the area takes place almost entirely by roads. There is no air services, river transport and railways serving the area. The principal forms of transport are road vehicles, pack animals and pedestrian traffic. Most movement occurs on hoof and foot, with the majority of goods carried to market as head-or back-loads.

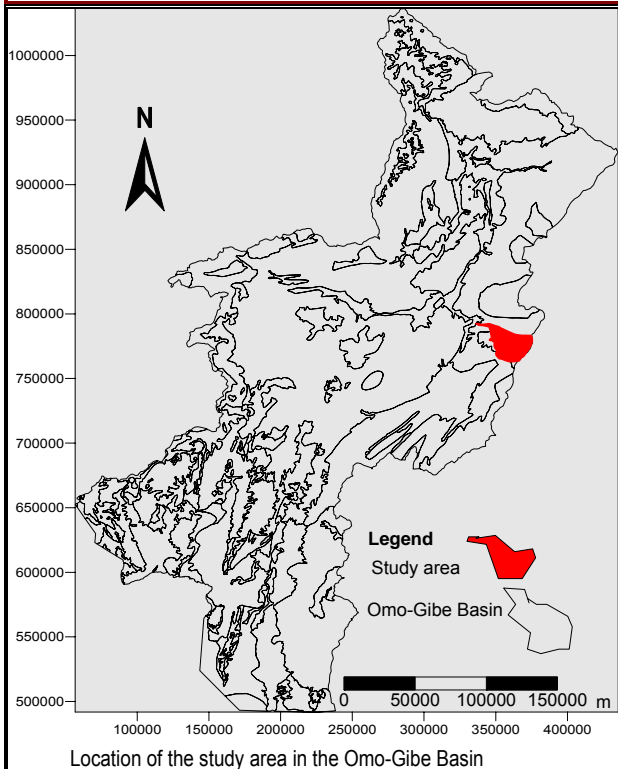
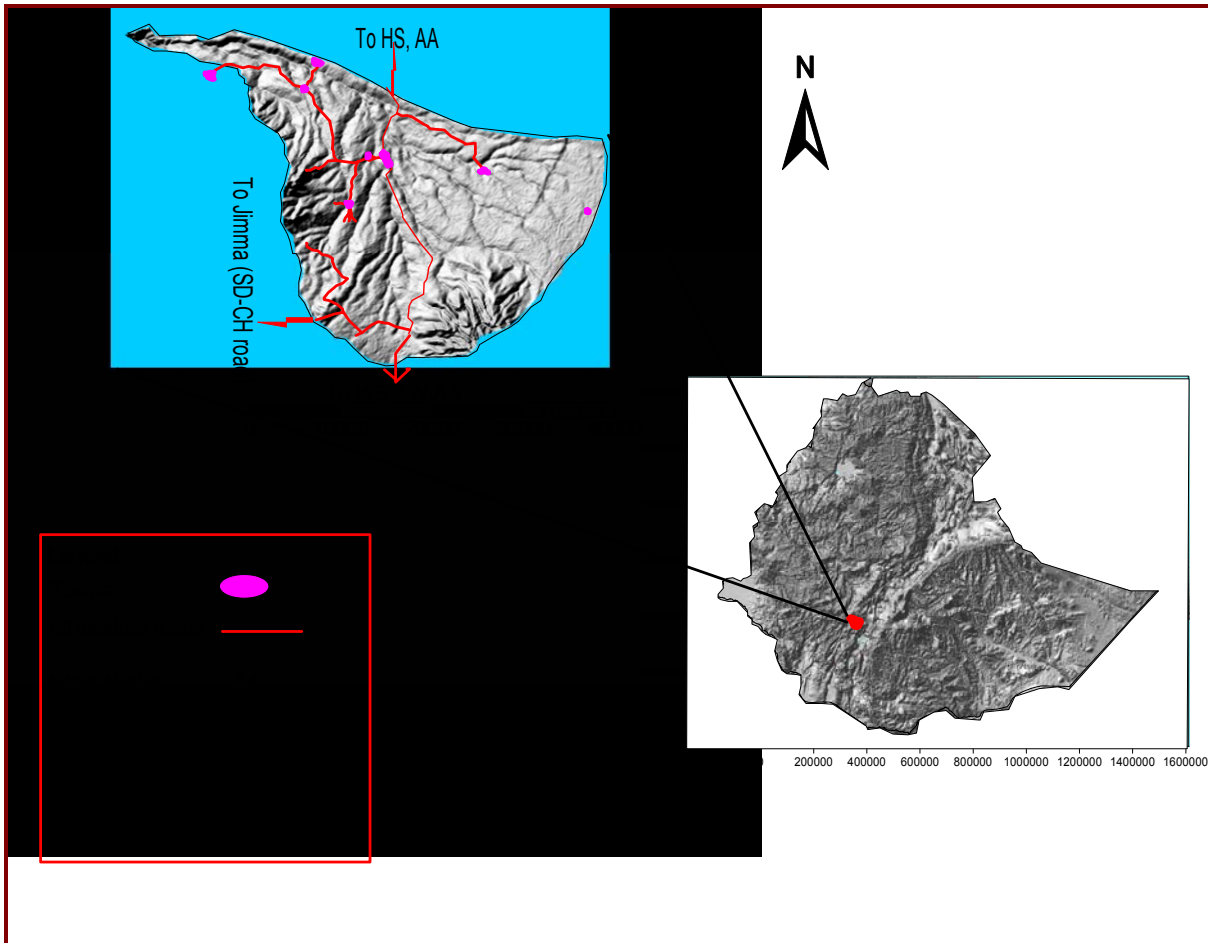


Fig 2.1 Location map of the study area

2.2 Climate

Climate of the study area ranges from semi-arid in the lowest Weybo valley to humid in the highest mount Damota with a greater portion of it is classified as semi-humid. The classification is made on the basis of the elevation above mean sea level of the areas.

Climatic variations are a function largely of land surface altitude. Precipitation in the catchment has strong seasonal and elevational variability. The primary wet season extends from April through October, July and August are the wettest months.

Average annual rainfall ranges from nearly 1081mm at the lowest altitudes to more than 1574mm above 2600m elevations. The mean annual precipitation of the catchment is computed to be 1341mm.

Temperature in the study area varies with altitude. For winter months, average monthly maximum temperatures are about 17°C in the mountainous areas and about 21°C in the low altitude areas near Ajora. Average monthly minimum temperature during winter ranges from 12°C at the south-eastern highlands to 14°C at the north-western low lands.

For summer months, average monthly maximum temperature range from about 22°C in the high areas to more than 28°C near Omo River.

In general, mean minimum and maximum temperature of the study area is about 12.8°C and 25.5°C respectively.

The maximum and minimum relative humidity of the area is calculated to be 49.7 and 77.3% respectively with a wind speed at 2m heights from the ground surface of 1.7m/sec minimum, and 3.2 m/sec, maximum.

The annual actual evapotranspiration rate of the catchment as computed from water balance studies of the area is 960.3 mm, with a maximum rate, in the month of April, is 132.9 mm and a minimum of 48.9 mm in January.

All sources of raw data are obtained from the national meteorological service agency of Ethiopia for each of the five meteorology stations of different classes with a minimum of 18 years data and one from the Ethiopian Agricultural Research Center found at Areka.

2.3 Physiography

Topographic relief of the study area is about 1840 from an altitude of about 1056m around the mouth of Weybo to 2896m near tip of mount Damota.

Most mountain ranges and the highest peaks (such as Afama ridge, Zamine ridge and mount Damota) in the catchment are on the basin boundaries.

About 50% of the area has a slope ranging from 2-6%, 25% has \approx 0-2%, 15% has \approx 6-12%, 6% has 12-24% and the remaining areas have a steep slope.

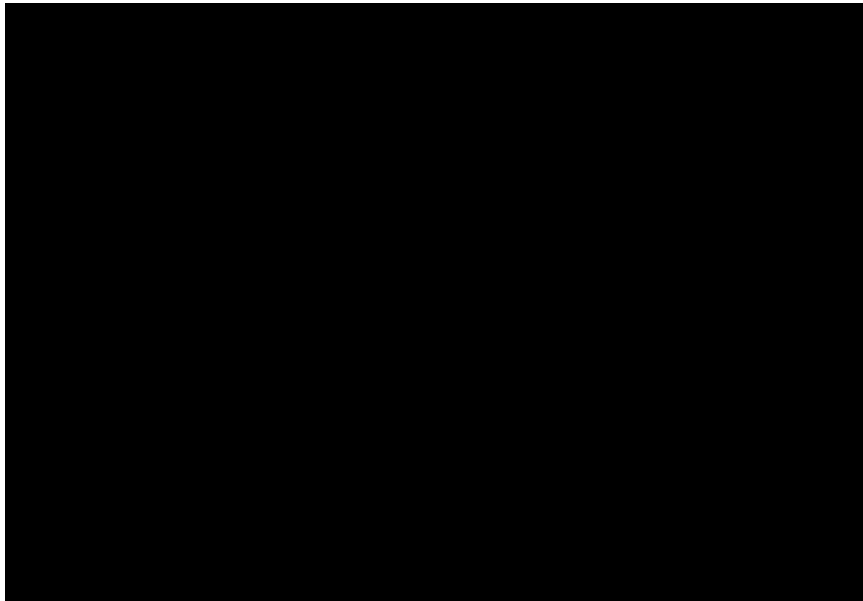


Fig. 2.2 Digital Elevation Model

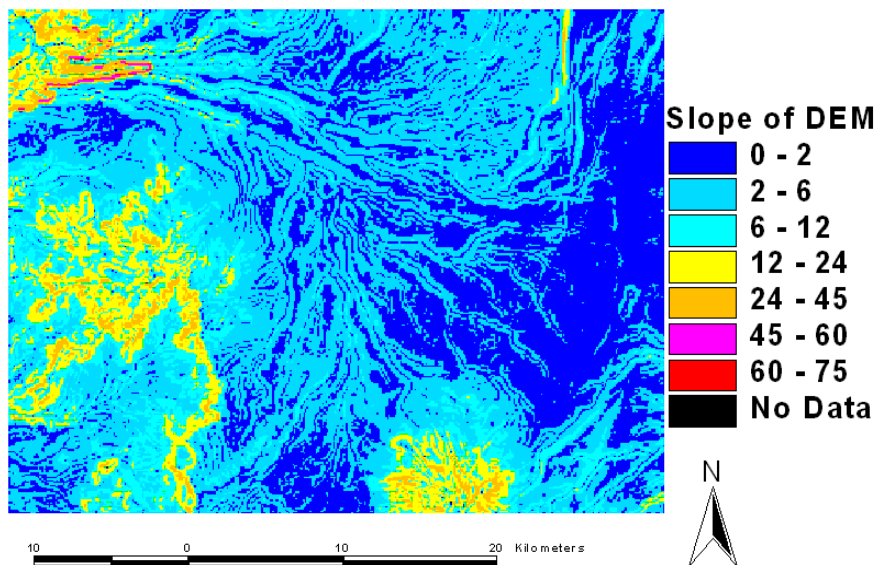


Fig. 2.3 Slope map of the area

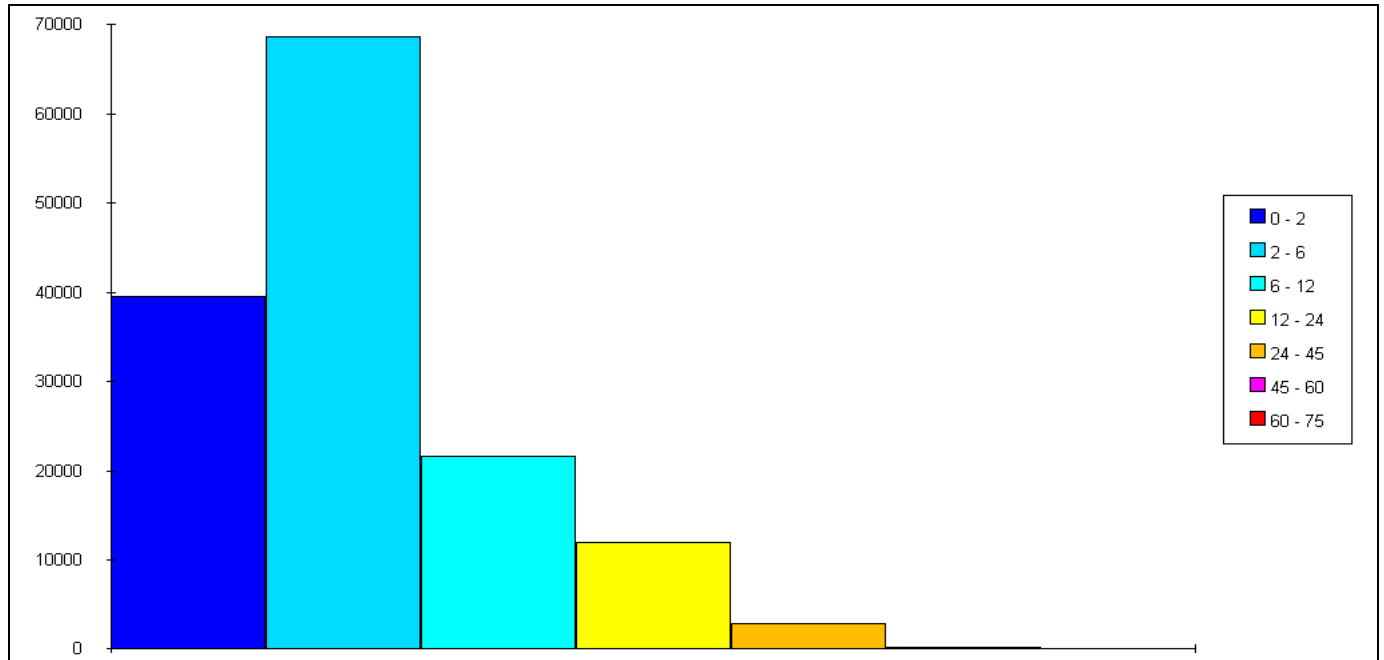


Fig. 2.4 Histogram of slope of DEM
 Note - Number of cells shown in vertical axis

The Weybo River originates in the Damota mountain and it flows about 52 Kms to the Omo River. Although the river is ephemeral along most of its length, it has perennial reaches at the headwaters in its lower part and north and north-eastern parts.

The drainage patterns of the tributaries are mainly dendritic and parallel in some parts and the drainage density of the catchment is about , and the main river is a 3rd order.

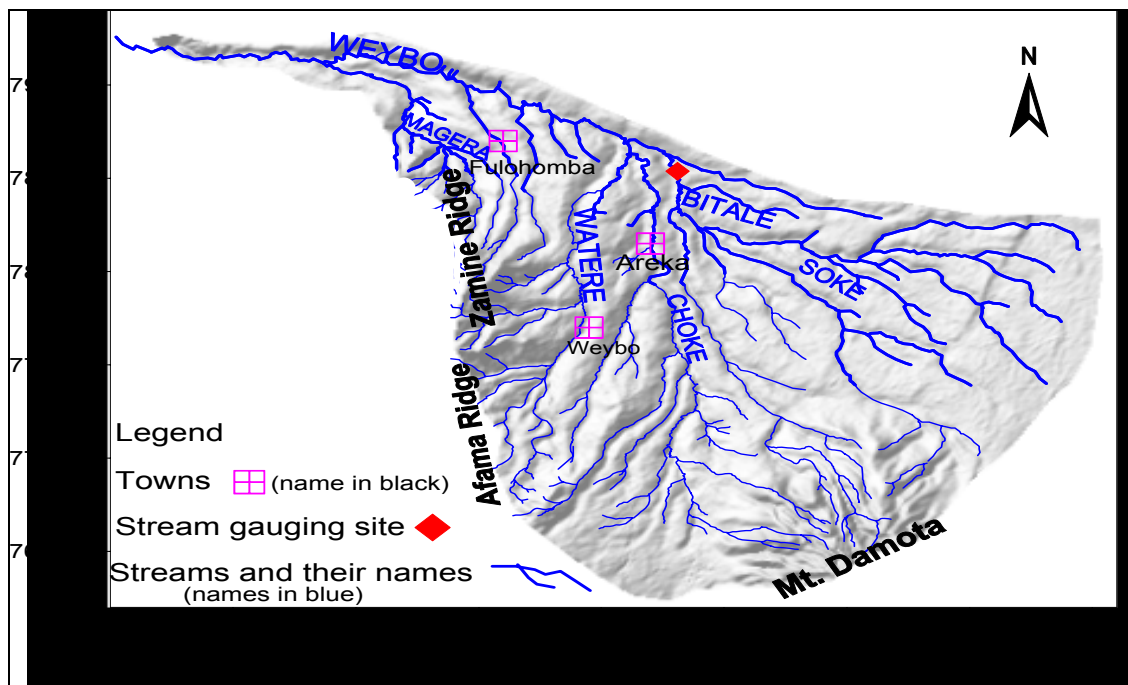


Fig-2.5 Drainage pattern of the study area plotted on a shaded relief map

3. Geology

3.1 Regional Geology

The basin, containing the study catchment-Omo-Gibe Basin, was a continental landmass during Paleozoic and Mesozoic times (Davidson, 1983). The geology of the basin can be sub-divided into four major groups of rocks, based on their age, relative to the formation of the rift valley system.

- The early 'Flood Basalts' of late Eocene to early Miocene age (20-40 my)
- A transitional series of intercalated basaltic and felsic volcanics of (?) late Oligocene to early Miocene; this unit also includes a sequence of volcanics and sedimentary rocks.
- A series of felsic volcanics ranging from (?) early Miocene (pre-rift) to late Miocene ('post rift') in age.
- The 'post rift' sedimentary succession of Pliocene to Holocene age (0-5 million years).

The various local basalt units that together make up the 'flood basalts' were described by Davidson, 1983, and included:

- Undifferentiated 'Flood basalt', in the central area - representing the thickest and most wide spread rock type of the tertiary volcanic sequence. They are the products of fissure eruptions and are characterized by thin, extensive flows, locally columnar jointed, or with jointing parallel to the flow layering. In places, the basalts include thin inter flow sediments, ignimbrites and minor felsic volcanics. They overlie the basal red sandstone (Paleozoic and Mesozoic) and where the sandstone is missing, they rest directly on the Precambrian basement.
- Makonnen Basalt in the north-west area - the name is given to the 700m thick sequence of columnar basalt that crops out to the east of the basin on the high plateau between the Baro and Akobo rivers. The basalts are aphyric or porphyritic, with plagioclase and olivine phenocrysts, and usually display columnar jointing. It ranges in age from 34.8 to 28.8 million years, and perhaps to 23.1 million years (Davidson, 1983).
- Surma basalt in the south-west area - the name given to the massive basalt flows that crop out on the Surma plain along the south-west water shed of the basin. Their age range is uncertain, although the single date from the Surma basalt gives a date of 19.4 million years (Davidson, 1983). In its localized occurrence in the south-west, the Surma basalt overlies the felsic volcanic units.
- Assille Group, sub divided into the Fejj basalt Langaria volcano-clastics and Bakate basalt in the south-east area (Davidson, 1983). The age range of this group is probably 32.8 – 20.0 million years (Davidson, 1983).

The Felsic Volcanics, Oligocene to Miocene

In parts of the basin where the geological relationships can be established clearly, the flood basalts are overlain by a series of more felsic volcanics although the latter includes intercalated basalts and pyroclastic rocks. Some rhyolites in this series in the southern part of the basin have been dated at 32.7 my old (Davidson, 1983), and in the extreme south-west the Surma basalt dated at 19.4my, overlies the felsic volcanics. However trachytes, rhyolites, and phonolite plugs and dykes, which are thought to be co-magmatic with the main felsic lavas, have been dated tentatively at about 13my old (Davison, 1983). These dates and stratigraphic relationships suggest that basaltic and more felsic lavas were being erupted contemporaneously from different volcanic centers, with a progressive evolution from basaltic to more felsic lava production. It is inferred that there was a period of transition between the (?) late Oligocene and early Miocene (bearing in mind this uncertainty with regard to absolute age).

The volcanic centers generally consist of an intrusive core, or plug, of massive rhyolite or trachyte surrounded by chaotic piles of coarse agglomerates and breccias that grade outwards to finer grained felsic ignimbrites (welded tuffs) and felsic tuffs (Moore and Davidson, 1978). There appears to be a gradual change in the composition of the felsic volcanics over time, from early rhyolite to quartz trachyte and finally to phonolite. The extrusive centers were strongly fault controlled and they often occur in clusters aligned along north-east trending fractures particularly along the axis of the Omo-Gibe Basin. The most prominent extrusive centers are from south-west to north-east: Mt. Naita; Ililbai Range; Mt. Mago; Mt. Dime; Mt Shasha; Mt Vennic; and Mt. May Godo (Mai Gudo).

Hypabyssal Intrusive rocks:

Many small intrusions of rhyolite, trachyte, phonolite micro-syenite and micro-granite occur throughout the basin, in the form of plugs and dykes ranging in size from 100m to 3.5 km in diameter. These intrude both the Precambrian rocks and the tertiary volcanic succession (Davidson, 1983), forming prominent round to conical hills that rise above the surrounding areas. These intrusive rocks appear to be co-magmatic with the surrounding felsic volcanics, however, they appear to show a wide range of ages (Davidson, 1983). Specifically, the phonolites yield ages of approximately 13 million years while other felsic plugs intruded volcanic flows dated at about 20 million years.

Nazareth Group, Miocene to Pliocene

The group name is assigned to the series of rhyolite-trachyte plugs stratoid flows, ignimbrites, pumice, ash fall tuffs and characteristic lacustrine sediments containing coal and lignite deposits along the main Ethiopian Rift and adjacent plateau margins. The Nazareth group attains a thickness of 200-300m in the Ethiopian Rift, but is thinner on the adjacent plateau margins. The ages of these rocks range from 10 to 3 million years (Kazmin, 1979; Kazmin et al., 1978, 1981). The group crops out along the north-east water shed of the basin over a large tract of land stretching from south of Weliso to Welkite - Hosaina - Sodo and Selam Ber, the rift escarpment, and unconformably overlies the early flood basalts, with minor intercalated basalts being found at the base of the group.

Rhyolite - Trachyt flows and ignimbrites

In the northern part of the basin, deposition of the younger sequences of the Nazareth group was accompanied by the formation of shield volcanoes of late Pliocene age (2-3 million years) on the main Ethiopian Rift escarpments (Kazmin et al., 1978, 1980). On the western escarpment, the volcanoes of Wachacha, Yerer, Gash Megel, Tembero, Damota and others, today form prominent landmarks. These young volcanoes are well preserved with little erosion of the cones and craters, and some contain small crater lakes. Several of these centers, Teza, Ambricho Wagebessa and Tembero, lie on a NNE alignment suggestive of formation along a major fault line. The ejecta from these volcanoes, both trachyte flows and felsic ignimbrites, cover the surface of the Ethiopian rift and most of the north-east watershed of the basin. The dominant rock type is a highly porphyritic trachyte with sanidine phenocrysts, which show flow structures.

3.2 Geological set-up of the study area

Identification and mapping of the lithological units and geological structures are majorly performed through field observations of river cuts, quarry sites, exposed mountain cliffs, dug wells and borehole logs, vegetation and drainage network patterns. These all are supported by interpretation and analyses of topographic maps (1:50000), satellite imageries (1:100,000), 3-dimensional digital elevation maps (1:100,000) and aerial photographs (1:50,000). The regional works of Davidson et al. 1983 and Kazmin et al. 1978, 1980 further supports these assessments.

3.2.1 Lithologic units and age

The main lithologic units that are outcropped in the study area and near to its adjacent watersheds are the tertiary volcanics.

According to the classification based on the ages of the units made by Davidson, 1983, the Nazareth Groups (of Miocene to Pliocene age) and the flood basalts (Eocene to early Miocene age) are the dominant units that widely cover the study area. By far, almost 90% of the area is covered by the Nazareth Group which comprises of a series of rhyolite-trachyt flows, ignimbrites, pumice and ash falls.

According to Davidson, 1983, the Nazareth Group attains a thickness of 200-300m in Ethiopian Rift, but is thinner on the adjacent plateau margins.

The Nazareth Group widely covers the southern, south-western, south-eastern and northern portions of the catchment where as the flood basalts crop out at the north-west tip of the study area. Based on the descriptions made by Davidson, 1983, the Nazareth Group unconformably overlies the early flood basalts with minor intercalated basalts being found at the base of the group.

The lithologic units in each part of the area under investigation are treated in the following way.

3.2.2 Descriptions and stratigraphic successions

Lower Weybo (Ajora and Imbecho)

Exposure of minor, dark colored, silica poor mafic rock, majorly basalt, at the bank of Weybo River. Textural analysis by the naked eye of the unit reveal a massive fabric and some parts of it show very small and narrow jointing. Top part of the rock show a slight to moderate weathering with a reddish clay product overlying the unit.

To a greater extent, felsic rocks, mainly rhyolite and rhyo-ignimbrites and pyroclastic tephra, majorly pumice are out cropped in association with the unit. From field observations and interpretations of satellite imageries, it is apparent that this area is a contact of the mafic and felsic units. The extent of the basaltic unit increases as one goes down to the confluence of Omo and Weybo rivers, where as the pyroclastic tephra are getting thinner and thinner and disappear at the confluence.

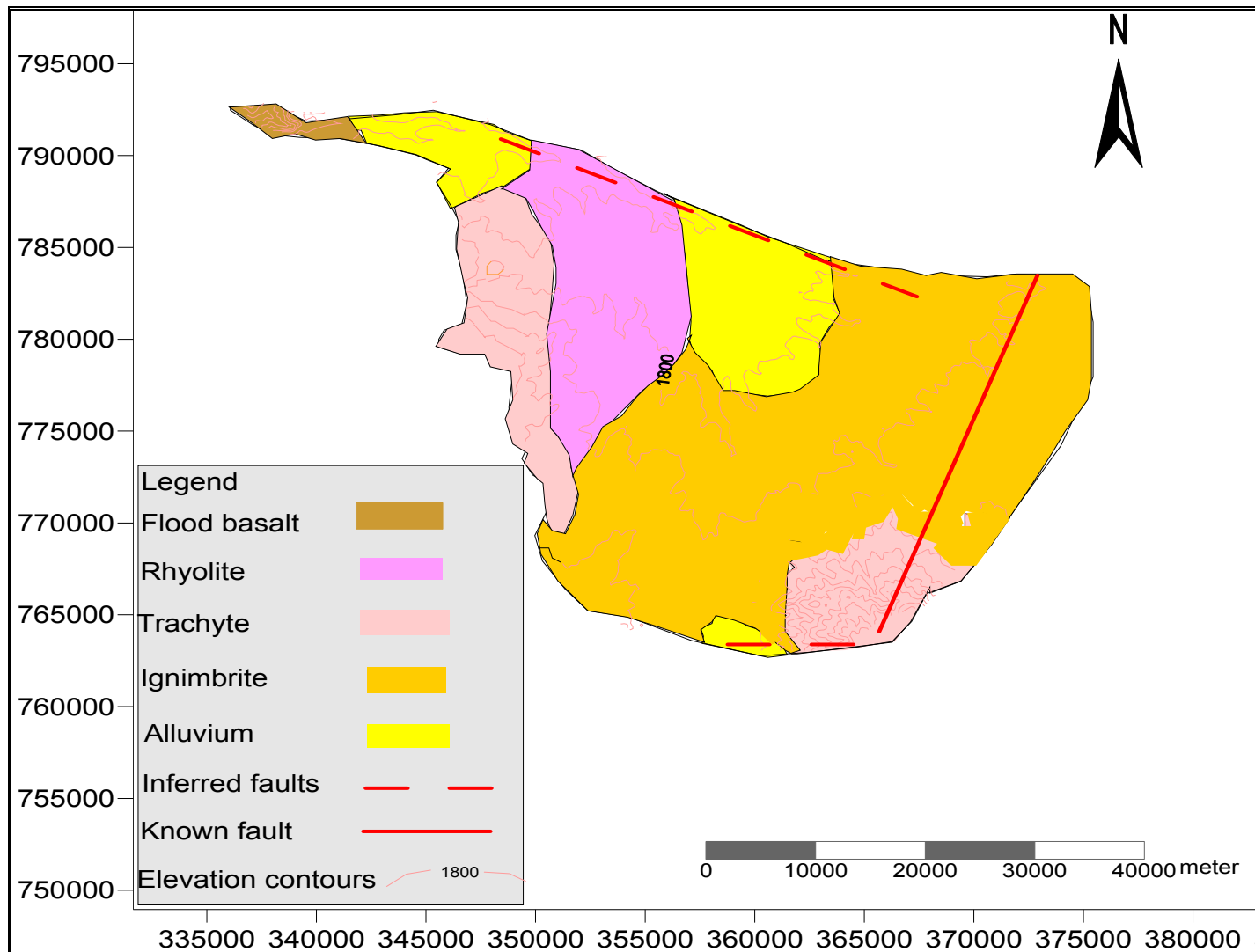


Fig 3.1 Geological map of the study area

3.2.3 Descriptions and stratigraphic successions

Dembazamine Ridge (1945 m.a.s.l.)

The south-western boundary of the catchment, Dembazamine ridge, and its adjacent plain is entirely covered by ignimbrites and unwelded tuffs. The units are overlain by a slightly weathered, light gray colored pumice. The surface of the ignimbrite shows moderate weathering and its degree of weathering decreases down depth as inferred from results of vertical electrical soundings. This unit extends northwards to join Afama ridge with a slight textural changes, in that it gets slightly massive, and eastwards to Oluchere plain. The eastward extension of the

unit follows the geomorphology of the area and it is surficially covered by sediments of about 8m thick. The degree of weathering and thickness of the weathered regolith of the unit show an appreciable increase from the ridge to Oluchere plain. Thickness of the pumice is also observed to increase eastwards.

Afama Ridge (2045 m.a.s.l.)

The western divide of the study area, Afama Ridge, is covered by rhyolite and rhyo-ignimbrite. The units in this specific location are characterized by fine texture, light gray colored and are fresh. These units are also exposed at the foot of the ridge and in north and north-east parts around Adila and Afama Michael villages. The fresh form of the unit in the later areas is attained at a variable depth of 40-150m.

Areka and its surroundings

An ignimbrite basement overlain by pumaceous deposit covers all Areka and its surrounding villages in all direction, Dubo, Doge, Sonkelle, Tadisa, Dola, Dengere and Wormuma. The top of those areas is covered by a dark brown silty clay soil with a variable thickness of 4m around Areka and 12m around Sonkelle and Dola. Deeply weathered ignimbrite and pumice units are dominating the central part of this area and the degree of weathering of both ignimbrite and pumice decreases outward the peripheries.

Gurumo Weyde quarry site (2025 m.a.s.l.)

Fresh, massive and light gray colored rhyolite associated with trachy – ignimbrite is exposed at the quarry site. This unit extends up to a ridge known as Gurumo Koisha. Foot of the ridge and areas westwards are covered by sediments transported from mount Damota and Gurumo Koisha. This unit is extended from mount Damota (2934m.a.s.l.), mountain with highest peak in the study area. And its emplacement is believed to be intrinsic to the formation of Damota Mountain.

Sorfella plain

The litho-units are not visible and exposed at the plain, however, signatures from vertical electrical soundings reveal that the plain is covered by a thick, $\approx 50\text{m}$, sediments, top of which is

dark brown clay and at road cuts slightly weathered pumaceous deposits. The Ignimbrite and/or rhyo-ignimbrite bed is expected to be encountered at a depth below 100m; which is believed to be an extension of the lower unit of mount Damota. A careful geological and geo-morphological investigation is recommended for further knowledge of the geology of the plain and its adjacent areas.

Eastern and (south – eastern) parts of the catchement

These parts of the catchement, including villages Gudicho, Suke, Admancho Girgira, Lera, Jarsohadena, Waritie, and Shento, are dominantly covered by welded tuff, and pumice associated with it. The tuff unit extends toward parts of the middle catchement and N-N-E wards where as the pumice widely covers both the middle and eastern portions of the study area.

Confluence of Ajora and Soke Falls

Fine grained and fresh, dark colored basalt is overlain by ignimbrite and pumice.

The extent of the lower basaltic unit increases down around the confluence of Ajancho and Omo river and a good surfacial exposure with a significant thickness is observed at the confluence.

Upper Omo River cut

Shattered basaltic cliff overlain by a thin ($\approx 3\text{m}$ thick) welded tuff is exposed at the eastern bank of Omo River. The tuff unit is disappeared immediately after crossing the river to the west and the basaltic unit is dominating westwards, the unit is overlain by a thin clay soil and a very localized, non-map-able pumaceous deposits. As one goes east and north-east wards away from the river cut along the newly constructed Sodo-Chida road and the old Gununo-Bele all weather roads, it is evident that the basaltic unit is disappearing and it is dominated by welded tuff and rhyolite which are overlain by pumice.

3.3 Geological structures

Minor and major tectonic structures have been identified within the catchement which all postdates the emplacement of the rock units. The identification of those structures had been

possible through interpretation of satellite imageries, 3-dimensional digital elevation maps and aerial photos, which are supported by field observations.

Thorough analyses of these tools show that the extent and orientations of the present structures are dictated/controlled by the predating structures.

Weybo – Soke Inferred Normal Fault

The drainage system of the major Weybo River is controlled by a normal fault with an orientation of NNW-SE that starts from the confluence of Weybo and Soke rivers and terminated by the normal fault system that runs from mount Jora (of Durame) to mount Damota (of Welaita).

This inferred fault acts as a catchement boundary (surface water divide) in the north and north-north-east portion of the study area.

Jora- Damota Normal Fault

The Jora- Damota normal fault system runs from Jora Mountain, Durame, and terminates at mount Damota of Welaita Sodo. It has NNE-SW orientation and a length of about 36 km. The fault is obscured by a wide spread volcanic product and sediments to have a direct field observation, however, observations of vegetation patterns and other superficial phenomenon and synergizing them with interpretations of 3-dimensional digital elevation maps greatly help confirm its existence.

Sorfella Fault system

A probable, obscured, fault running from west to east bounded by Afama ridge from west and Gurumo Koisha ridge from east having a lateral extent of 11 kms is inferred. Its existence is inferred from drainage systems in the catchement and the southern neighbouring catchement and analyses of results of vertical electrical soundings.

This fault system acts as a boundary for the southern part of the study area; and it needs further investigation and assessment through employing other techniques such as lateral inhomogeneity hunting (profiling).

Choke minor faults

Minor fault structures (not map-able) have been visually observed around choke stream, near Killo spring, which has been interpreted by missing lithologic units.

4. Hydrometeorology

4.1 General

Meteorological data are used as a basis for the study of rainfall, runoff, evaporation and transpiration, and hence, are among the crucial tools for water resources investigation.

There are six functioning meteorology stations distributed within and around the study area. Two of which are of the kind - class A, and the remaining four are ordinary types. 16-30 years mean monthly data of the meteorological elements for each of the stations have been collected from the National Meteorological Service Authority (Ethiopia).

The main Weybo River is not gauged at its mouth; and stream flow data is obtained from the gauging station installed at one of its tributaries (look at fig.2.3). 16 years flow records are collected from the Ministry of Water Resources (Ethiopia) for the analogue catchment.

4.2 Annual effective areal depth of precipitation

Although there are no very significant variations of precipitation in the catchment and its surroundings, it is necessary to obtain the effective uniform depth of precipitation for the catchment to obtain a more reliable and representative result.

Because of the non-uniform distribution of the precipitation gauges (Fig-4.1) the Thiessen polygon method is preferred to the simple arithmetic method. The non-uniformity and the less number of the stations favor not to adopt the isohyetal method of quantifying areal depth of precipitation. However, the variations of the precipitation depths in each of the stations is not highly pronounced and the geomorphology of the study area do not show a significant change with its surroundings in slope, three of the methods are applied to quantify and then compare the results.

The normal ratio method has been adopted to fill short breaks in records, i.e. precipitation is estimated from that observed at three stations are as close to and as evenly spaced as possible around the station with the missing record.

The Thiessen polygon method

This method calculates the weighted average of each precipitation station in and near the catchments based on the following relationship.

$$PPT = \sum(A_i/A) P_i, i = 1-n$$

Where P_i is the precipitation of the i^{th} gauge, A_i is the area of the specific polygon bisected by using the Thiessen method corresponding to the precipitation P_i (Fig 4.1), A is the total area of the catchment, i refers to the i^{th} precipitation gauge and n is the number of the Thiessen polygons.

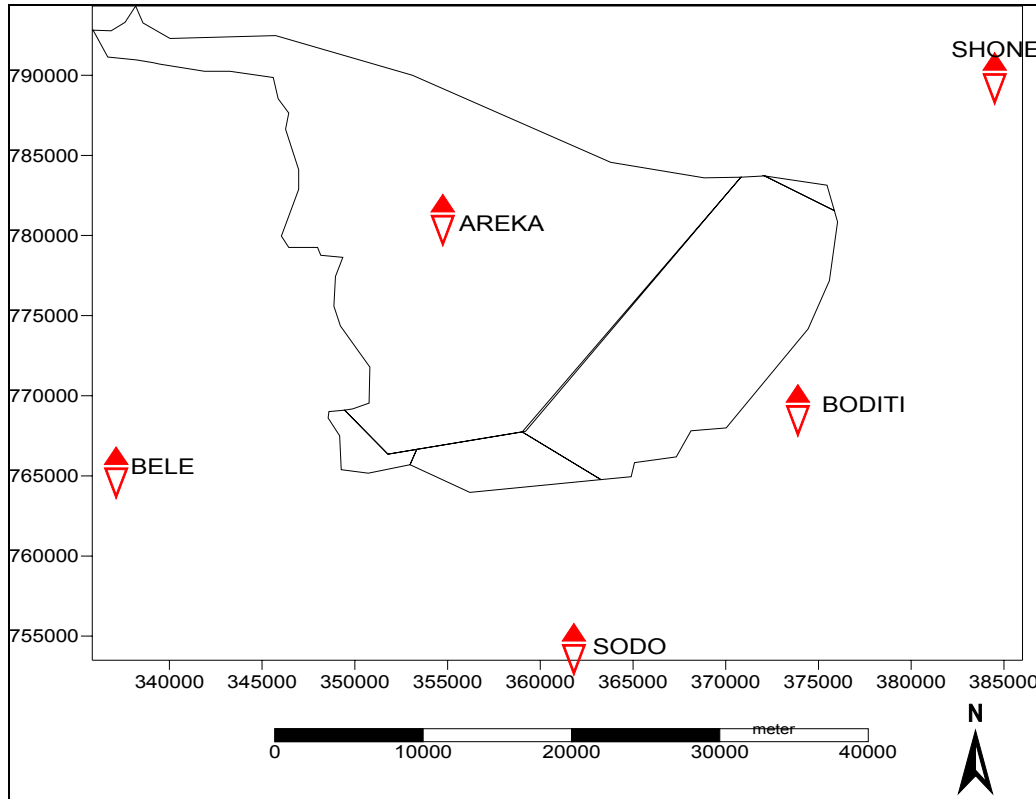


Fig.4.1 Thiessen polygons and locations of meteorological stations

Accordingly, the aerial depth of precipitation of the catchment is calculated and resulting values are presented in table below.

Table 4.1 Mean annual depth of precipitation obtained from Thiessen-Polygon method

Station	Area (Km ²)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Areka	380.0	42.29	67.20	101.7	185.6	172.2	142.8	202.1	200.9	180.7	126.9	28.42	29.53	1480.2
Bele	8.5	36.64	35.51	70.0	129.9	140.3	129.4	158.1	177.5	129.7	86.4	49.41	38.81	1081.6
Boditi	161.0	31.62	53.82	99.2	160.8	154.8	138.4	156.1	153.4	110.3	88.1	37.22	36.16	1220.0
Shone	2.6	50.91	69.61	132.5	211.0	180.6	141.4	183.5	205.3	185.1	121.7	45.66	47.63	1574.9
Sodo	23.4	34.34	47.26	68.3	151.0	156.9	118.8	163.2	167.4	86.3	96.3	49.26	37.62	1176.5
Total	575.5	38.94	61.66	50.1	176.5	166.3	140.4	186.9	185.9	156.4	114.2	32.12	31.93	1341.3

AVERAGE ANNUAL PRECIPITATION OF THE STUDY AREA = 1341.3mm

The arithmetic mean

For the reasons mentioned earlier, the areal depth of precipitation of the catchment has also been quantified using the arithmetic mean. Table Below shows the mean monthly uniform areal depth of precipitation calculated using the arithmetic mean method

Table 4.2 mean monthly areal depth of precipitation obtained from arithmetic mean

Stations	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Total
Areka	42.29	67.20	101.66	185.61	172.15	142.81	202.10	200.85	180.70	126.87	28.42	29.53	1480.19
Sodo	34.34	47.26	68.28	150.97	156.86	118.76	163.23	167.38	86.30	96.31	49.26	37.62	1176.54
Bele	36.64	35.51	70.01	129.86	140.26	129.43	158.09	177.52	129.74	86.38	49.41	38.81	1081.67
Boditi	31.62	53.82	99.22	160.80	154.84	138.36	156.13	153.44	110.26	88.13	37.22	36.16	1219.98
Shone	50.91	69.61	132.53	210.97	180.63	141.41	183.47	205.30	185.13	121.71	45.66	47.63	1574.93
Total	195.80	273.39	471.69	838.21	804.74	670.75	863.01	904.47	692.12	519.39	209.96	189.73	6633.27
Mean	39.16	54.68	94.34	167.64	160.95	134.15	172.60	180.89	138.42	103.88	41.99	37.95	1326.65

The isohyetal method

The method is employed by preparing an isohyetal map, which is prepared by plotting the precipitation station locations and precipitation amounts on a suitable chart, and by drawing contours of equal precipitation. One advantage of the method for determining catchment averages is that it allows the influence of physiographic parameters to be taken in to account. These factors include elevation, slope, and distance from the coast and exposure to rain-bearing winds (Shaw, 1988). The method yields an annual mean precipitation of 1350.3mm.

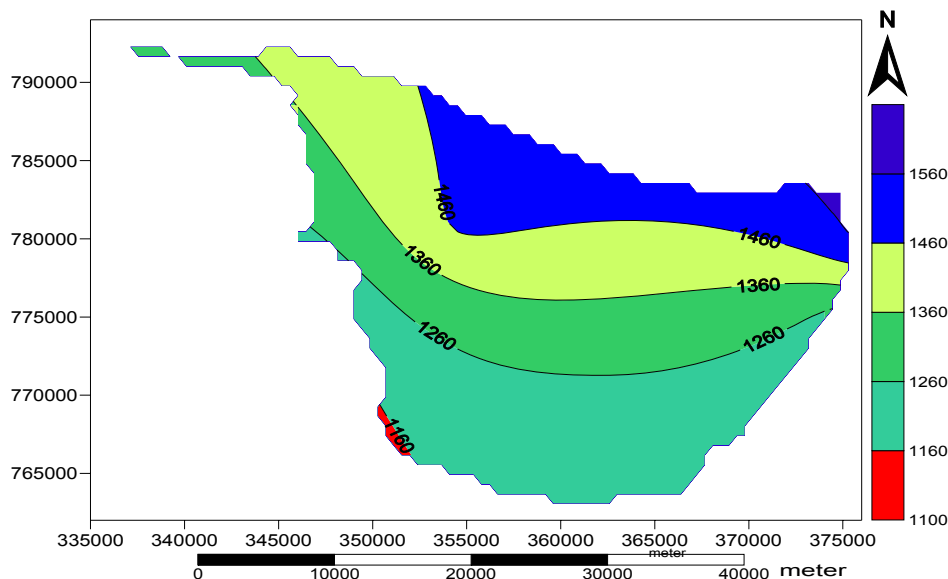


Fig. 4.2 Isohyets and spatial variations of depth of precipitation

Three of the methods result in more or less similar values, which is in good agreement with the aforementioned justifications. The mean annual precipitation of the catchment is taken to be 1341, which is the median of the three values.

4.2.1 Relationships between surface elevation and depth of precipitation

Among the many factors that control the depth and distribution of precipitation in a given water shed, effects of surface elevation could be manifested in multi-ways.

In the study area, precipitation and surface elevation display a direct positive correlation.

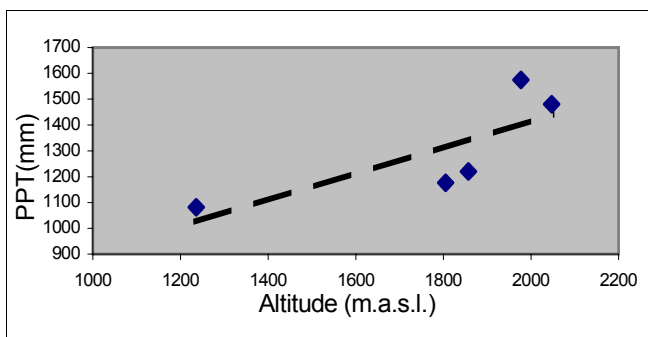


Fig. 4.3 Relationship between altitude and depth of precipitation

Station Name	Altitude (m.a.s.l.)	PPT depth (mm)	Correlation Coefficient
Shone	1977	1574.93	0.783
Areka	2047	1480.19	
Boditi	1857	1219.98	
Sodo	1805	1176.54	
Bele	1236	1081.63	

Table 4.3 Correlation coefficient Between ppt and altitude

4.2.2 Rainfall coefficient

Months are partitioned into rainy and dry in the given hydrologic year based on the values of rainfall coefficients.

Rainfall coefficient is the ratio between the mean monthly rainfall depth and one-twelfth of the mean yearly rainfall.

It is given by the formula,

$$R_C = P_m / (P_Y / 12) \quad \text{Where } R_C = \text{Rain fall coefficient, } P_m = \text{Mean monthly rainfall depth}$$

$$P_Y = \text{mean yearly rainfall depth}$$

A month is considered to be "rainy" when the corresponding monthly rainfall coefficient reaches 0.6 and distinctly rainy when it exceeds 0.8. Extremely rainy months may have a coefficient of more than 1 (Daniel 1977).

The following table shows the rainfall coefficients for the weighted mean of precipitation of the study area.

Table 4.4 monthly rainfall coefficients for the study area

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
P_m (mm)	38.94	61.66	50.12	176.5	166.3	140.4	186.9	185.9	156.4	114.2	32.12	31.93
R_c	0.35	0.55	0.45	1.58	1.49	1.26	1.67	1.66	1.40	1.02	0.29	0.29
$P_Y=1341$												
$P_Y/12 = 111.78$												

P_m (mm) = mean monthly rain fall depth in mm

R_c = rain fall coefficient

P_Y = mean yearly rainfall depth in mm

On the basis of the rainfall coefficient values, months in the water year are classified as

- i) Dry months: November, December, January and February
- ii) Rainy months: March, April, May, June, July, August, September and October

The following table gives a broad classification of months of a water year (after Daniel, 1977).

Table 4.5 Classification schemes of monthly rainfall values

	Dry months	Rainy months			
		Small rains	Big rains		
			Moderate C	High C	Very high C
	$R_c < 0.6$	$0.6 < R_c < 0.9$	$1 < R_c < 1.9$	$2 < R_c < 2.9$	$R_c \geq 3$
Months	November, December, January February March		April, May, Jun, July August September October		

C refers concentration

The dry months contribute only about 12.27% of the total mean annual rainfall to the area where as the remaining 87.73% of the total mean annual rainfall is contributed by the rainy months.

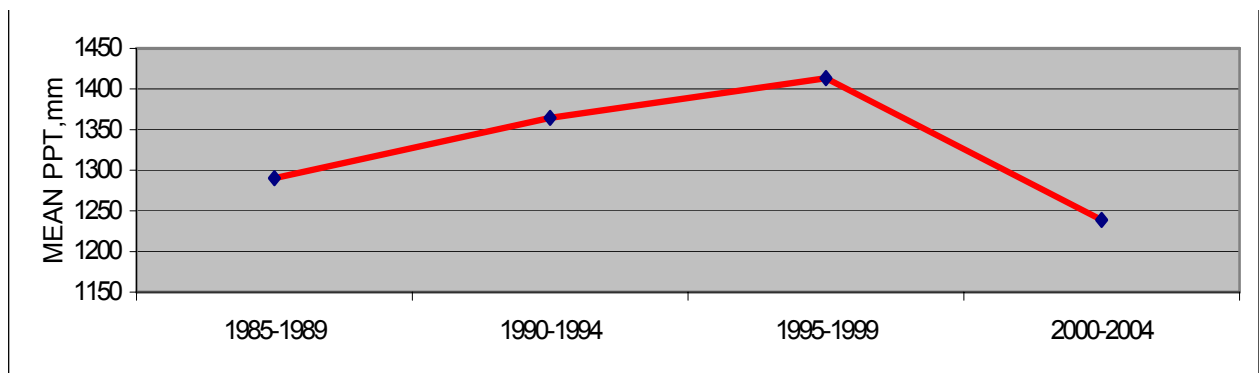


Fig 4.4 Five years-aggregate trend of precipitation, 1985-2004

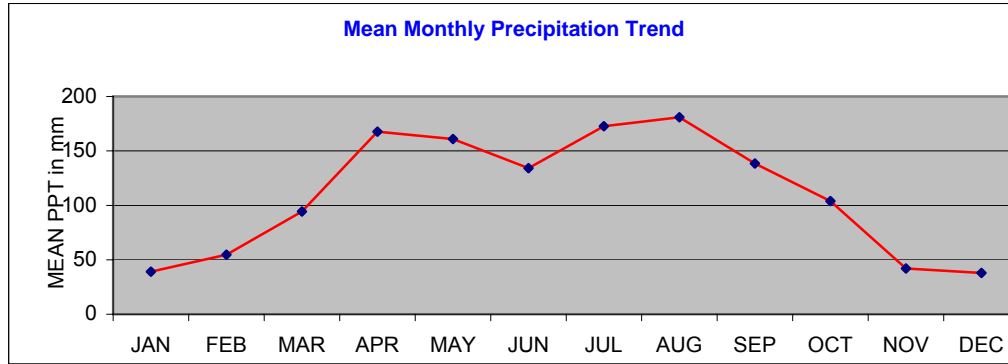


Fig 4.5 Monthly precipitation trend

4.3 Temperature

The temperature of the water surface is important in that it governs the rate at which water molecules leave the surface and enter the overlying air, a change in water surface temperature may, therefore, have a profound short-term effect up on the rate of evaporation.

Table 4.6 Mean maximum and minimum temperatures of the study area

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	AVERAG
M.M.T.S.A.	26.39	27.42	27.42	27.42	27.42	27.42	21.52	21.83	23.42	24.41	25.90	26.13	25.56
M.Mi.M.T.S.A.	13.00	13.80	14.05	14.00	13.72	13.18	12.44	12.43	12.45	12.28	14.75	12.10	12.86
M.M.T.T.S.A.	19.70	20.61	20.73	20.71	20.57	20.30	16.98	17.13	17.94	18.34	20.32	19.11	19.21

M.M.T.S.A. = Mean monthly temperature of the study area
M.Mi.M.T.S.A. = Mean monthly minimum temperature of the study area
M.M.M.T.T.S.A. = Mean monthly maximum temperature of the study area

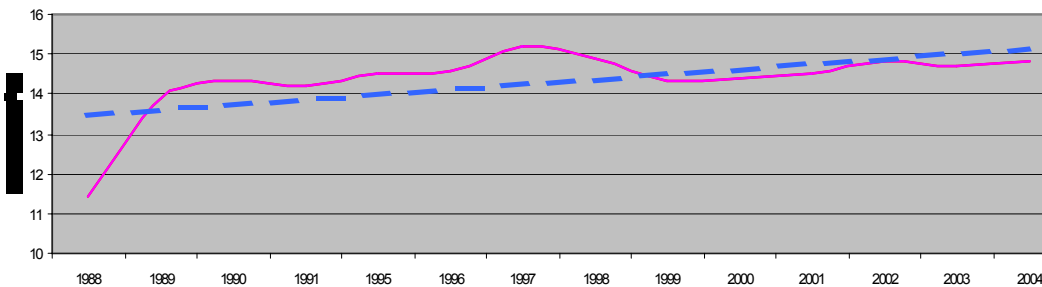


Fig 4.6 Increasing trend of mean temperature

4.4 Relative humidity

Relative humidity is one of the more variable characteristics among the meteorologic elements. As it rises, proportionately fewer of the water vapor molecules leaving the evaporating surface can be retained in the air, and so the rate of evaporation, i.e., the total number of molecules leaving, minus the total number of molecules returning, is gradually reduced.

Table 4.7 Mean monthly relative humidity of the study area (%)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Average (annual)
Monthly average	53.1	51.5	54.9	64.4	72.6	74.2	77.3	75.8	75.7	63.6	49.8	52.8	63.8

4.4 Wind speed

Evaporation from a free water surface in to a completely still layer of air will be continually slowed down as the air layer approaches saturation point, and as more of the water vapor molecules in the air re-enter the water surface. Some sort of air movement is, there fore, necessary to stir up the air and to remove the lowest moist layers in contact with the water surface and to mix them with the upper drier layers. So that the rate of evaporation is almost always influenced to some extent by air movement.

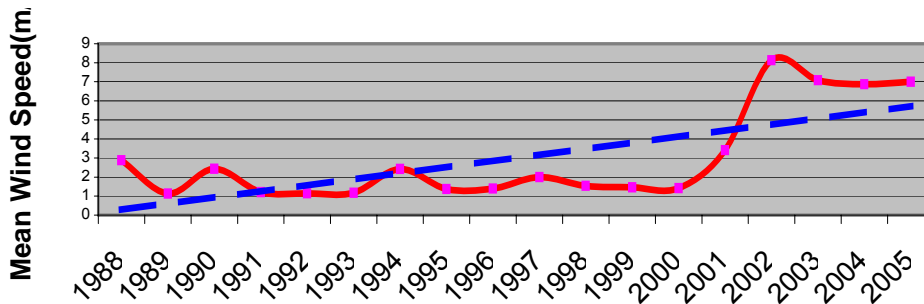


Fig. 4.7 Increasing trend of wind speed

Table 4.8 Mean monthly wind speed above 2m from ground surface, of the study area

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Average (annual)
Station-1	3.581	3.856	3.602	3.300	2.581	2.289	1.901	1.973	1.749	2.243	3.586	3.862	2.877
Station-2	2.454	2.325	2.065	1.718	1.480	1.425	1.834	1.433	1.430	1.724	2.651	2.604	1.930
Station-3													
Average	3.017	3.091	2.834	2.509	2.030	1.857	1.868	1.703	1.590	1.983	3.118	3.233	2.403
M.W.S.S.A.	3.017	3.091	2.834	2.509	2.030	1.857	1.868	1.703	1.590	1.983	3.118	3.233	2.403

M.W.S.S.A. = Mean wind speed of the study area (m/s)

4.5 Evapotranspiration

A quantitative understanding of evapotranspiration is of vital practical importance in several respects: over the long term, the difference between evapotranspiration and precipitation is the water available for direct human use and management. Thus quantitative assessments of water

resources and the effects of climate and land-use change on those resources require a quantitative understanding of evapotranspiration.

Direct measurement of evapotranspiration is much more difficult and expensive and is usually impractical. Thus an array of methods has been developed that provide estimates of evapotranspiration based on measurement of more readily measured quantities.

4.6.1 Potential evapotranspiration (PET)

Thornthwaite, 1948, conceptually define potential evapotranspiration (PET) as the rate at which evapotranspiration would occur from an area completely and uniformly covered with growing vegetation which has access to an unlimited supply of soil water and with out advection or heat storage effects. And according to Jensen et.al.,1990, operational definition, practically PET is defined by the method used to calculate it, and many methods have been proffered.

These methods can be classified on the basis of their data requirements (Jensen et. al., 1990) as temperature based, that uses only air temperature and some times day length; radiation based, that uses net radiation and air temperature; combination, based on the Penman combination equation which uses net radiation, air temperature, wind speed and relative humidity; and pan, that uses pan evaporation, some times with modifications depending on wind speed, temperature, and humidity.

4.6.1.1 Penman or combination approach

Because it gives satisfactory results (Van Bavel, 1966) and it has a theoretical foundation, and it requires meteorologic inputs that are widely available or can be reasonably well estimated from available data, the combination method has been adopted to quantify the PET of the study area.

Below is mean monthly PET of the catchment calculated using the combination approach.

Table 4.9.

Table 4.9 Mean annual PET obtained from Penman method

ELEMENTS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	(ANNUM)
T (°C)	19.7	20.61	20.73	20.71	20.57	20.3	16.98	17.13	17.94	18.34	20.32	19.11	
n(Hrs)	8.07	8.68	7.58	12.18	7.42	5.17	3.43	3.76	5.74	7.39	8.69	8.94	
N (Hrs)	11.7	11.9	12	12.2	12.5	12.6	12.4	12.4	12.1	11.9	11.7	11.6	
n/N	0.689	0.729	0.632	0.998	0.593	0.41	0.277	0.303	0.474	0.621	0.743	0.771	
H (%/100)	0.53	0.515	0.549	0.644	0.726	0.742	0.773	0.758	0.757	0.636	0.498	0.528	
U1 (m/s)	3.017	3.091	2.834	2.509	2.03	1.857	1.868	1.703	1.59	1.983	3.118	3.233	
U2 (miles/h)	6.75	6.916	6.34	5.614	4.542	4.155	4.179	3.81	3.557	4.436	6.976	7.233	
E _a (mmHg)	17.01	18.105	18.12	18.108	18.1	18.08	14.53	14.71	15.49	15.73	18.083	16.48	
E _d	9.015	9.324	11.452	11.662	13.14	13.415	11.23	11.15	11.73	10	9.005	8.701	
Δ/γ	2.192	2.298	2.311	2.309	2.293	2.263	1.887	1.904	1.983	2.022	2.265	2.122	
R _a (mm/day)	14.6	15	15.2	14.7	13.9	13.4	13.6	14.3	14.9	15	14.6	14.3	
E _{at}	2.987	3.286	2.482	2.383	1.815	1.701	1.203	1.293	1.363	2.094	3.399	2.92	
R _i (1-r)	6.428	6.885	6.293	8.588	5.504	4.161	3.386	3.732	5.073	6.131	6.8	6.843	
R _o	4.448	2.849	2.303	3.272	1.997	1.497	1.24	1.324	1.723	3.416	2.897	2.959	
f _a (n/N)	0.587	0.612	0.552	0.779	0.528	0.414	0.332	0.348	0.454	0.545	0.621	0.638	
σT _a ⁴	15.138	15.251	15.34	15.325	15.221	15.022	14.183	14.309	14.352	14.672	15.036	14.685	
H _T	1.98	4.036	3.99	5.316	3.507	20664	2.146	2.408	3.35	2.715	3.903	3.884	
PET (mm/day)	2.295	3.809	3.535	4.43	2.993	2.369	1.809	2.024	2.684	2.542	3.749	3.575	
PET (mm/month)	68.85	114.27	106.05	132.9	89.79	71.07	54.27	60.72	80.52	76.26	112.47	107.25	1074.42

PET = Potential Evapotranspiration

$$PET = [(\Delta/\gamma)H_T + E_{at}]/(D/g) + 1$$

$$H_T = R_i (1-r) - R_o$$

$$R_i (1-r) = 0.75R_a * f_a (n/N)$$

$$f_a (n/N) = 0.16 + 0.62n/N$$

$$R_o = \sigma T_a^4 (0.47 - 0.075\sqrt{e_d})(0.17 + 0.83n/N)$$

$$E_{at} = 0.35(0.5 + u_2/100)(e_a - e_d) = f(u)(e_a - e_d)$$

$$r = \text{albedo}$$

e_a = the saturated vapor pressure at air temperature, T_a

e_d = the saturated vapor pressure at the dew point, T_d, e_a - e_d = the saturation deficit

Δ = the slope of the curve of saturated vapor pressure plotted against temperature

γ = hygrometric constant (0.27mmHg/°F), R_i = incoming radiation, R_o = outgoing radiation

R_a = the solar radiation (fixed by latitude and season)

σT_a⁴ = the theoretical black body radiation at T_a

σ = the Stephan Boltzman Constant, = 5.67 * 10⁻⁸Wm⁻²/K⁴

u₂ = mean wind speed at 2m above the surface, miles/day

E_a = energy for evaporation based on the air humidity and air temperature

T_a = mean air temperature for a month, °C

n = bright sunshine over the same period, h/day, H_T = the available heat

N = mean daily duration of maximum possible sunshine hours (South Latitudes)

4.6.1.2 Pan evaporation approach, penman 1, 1950a

The method relates potential evapotranspiration from a vegetated land surface to the evaporation from open water, (penman, 1950a).

Pans provide an observation of effects of radiation, wind, temperature and humidity on evaporation, all integrated together, from an open surface the response of plants is in the same fashion. But heat storage, reflectivity, air turbulence, temperature and humidity of the plant and pan vary widely. All these factors are included in the pan coefficients from many observational researches on the effect of climate on crop evapotranspiration (UNESCO, 1987).

The appropriate value of pan coefficient is selected based on the ground cover of the pan station and its surroundings and general wind and humidity conditions (FAO, 1977). Accordingly, for the mean relative humidity range of 40-70% (medium), mean speed of 24 hour wind ranging from 175-425 km/day (moderate), and pan station surrounded to a distance of 10 -100m by green crop in the wind ward side, the pan coefficient, f, is determined to be 0.75 (FAO, 1977).

Based on this method, PET of the study area is calculated and yields the following mean monthly values of PET.

Table 4.10 Mean monthly values of PET obtained from pan evaporation

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Annual
Monthly mean	120.91	114.14	103.15	90.42	69.48	62.56	41.21	43.19	45.88	92.29	118.62	113.22	1015.07

4.6.1.3 Thornthwaite approach

The formula is based mainly on temperature with an adjustment being made for the number of day light hours. An estimate of the potential evapotranspiration, PET, calculated on a monthly basis, is given by:

$$PET_m = 16N_m(10\check{T}_m/I)^a \text{ mm}$$

$$I = \sum i_m = \sum (\check{T}_m/5)^{1.5}$$

Where $a = 6.7 \cdot 10^{-7} I^3 - 7.7 \cdot 10^{-5} I^2 + 1.8 \cdot 10^{-2} I + 0.49$ (to 2 significant digits)

N_m (day light factors) is obtained by dividing the possible sunshine hours for the appropriate latitude by 12 (it is the monthly adjustment factor related to hours of daylight)

m = months in a year 1,2,3 ---12, \check{T}_m = monthly mean temperature, °C,

I = the heat index for the year

Table 4.11 Mean annual PET obtained from Thornthwaite method

Element	Months												TOTAL
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
\bar{T}_m (°C)	19.7	20.61	20.73	20.71	20.57	20.3	16.98	17.13	17.94	18.34	20.32	19.11	
N	11.7	11.9	12	12.2	12.5	12.6	12.4	12.4	12.1	11.9	11.7	11.6	
Nm	0.975	0.992	1	1.0167	1.0417	1.05	1.033	1.033	1.008	0.992	0.975	0.967	
im	7.82	8.369	8.442	8.43	8.344	8.181	6.258	6.341	6.796	7.025	8.193	7.472	
I	91.671												
a	2.01												
PETm	72.596	80.88	82.489	83.702	84.601	83.04	57.06	58.07	62.184	63.97	77.262	67.73	873.584

From the above three results, the PET obtained from Penman combination method seems to be representative. Thornthwaite method underestimates the value, and pans are not monitored/controlled properly in the field as it is observed during field visits even though the values are nearly similar to that obtained from penman. Therefore, for further analyses the catchment's PET is assumed to be 1074.42.

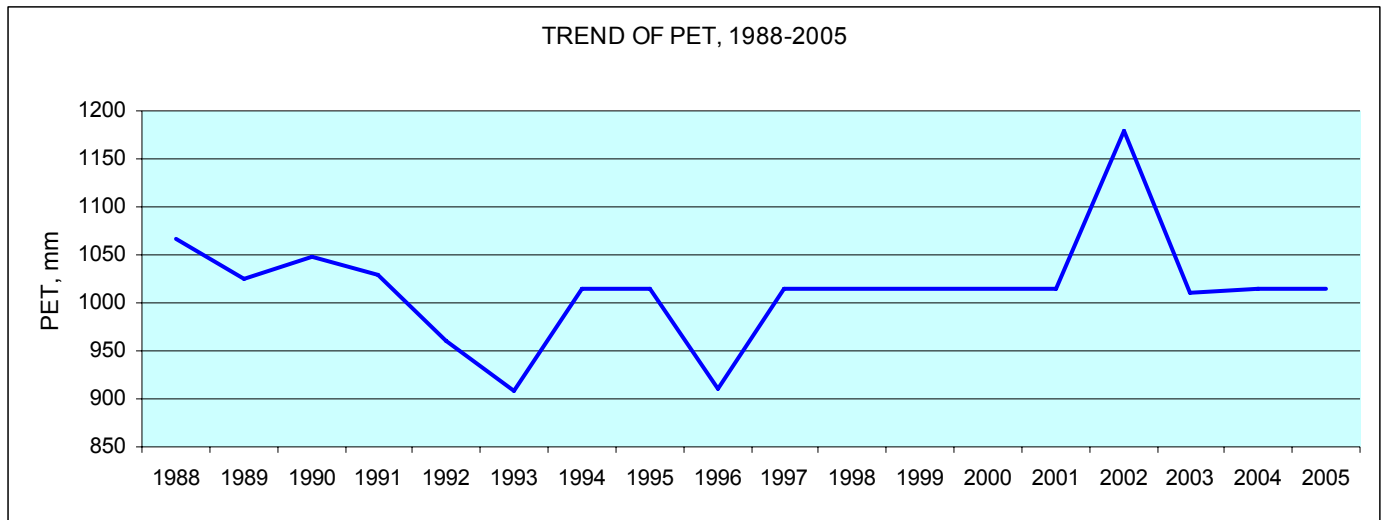


Fig 4.8 Trend of potential evapotranspiration, 1988 - 2005

4.6.2 Actual evapotranspiration (AET)

Water loss from a catchment area does not always proceed at the potential rate, since this is dependent on a continuous water supply.

Actual evapotranspiration is used to describe the amount of evapotranspiration that occurs under field conditions (Thornthwaite, 1944).

4.6.2.1 Quantification of actual evapotranspiration (AET)

4.6.2.2 Obtaining AET from PET

A Value of the actual evapotranspiration (AET) over a catchment is more often obtained by first calculating the potential evapotranspiration, i.e., assuming an unrestricted availability of water, and then modifying the results by accounting for the actual soil moisture content. When the vegetation is unable to abstract water from the soil, then actual evapotranspiration becomes less than potential. Thus, the relationship between AET and PET depends up on the soil moisture content. When the soil is saturated, i.e. when it is at its field capacity, PET = AET (Shaw, 1984).

The value of AET obtained from measurements of PET is about 960.3mm/year and procedures and results are presented in soil-water balance (Thornthwaite and Mather, 1957) section of this thesis.

4.6.2.3 Empirical formulae

4.6.2.3.1 Formula developed by Turc (1954, 1955)

$$AET = P/[0.9 + (P/L)^2]^{1/2} \text{ mm per annum}$$

Where P= mean annual precipitation (mm)

$$L = 300 + 25T + 0.05T^3$$

T= mean are Temperature ($^{\circ}$ C)

$$AET = 884.96\text{mm/year}$$

4.6.2.3.2 Formula developed by Thornthwaite (1948)

$$AET = [11.5 (P/T - 10)^{1/9}]^{-1} * P$$

Where P = precipitation in inch, T = temperature in $^{\circ}$ F, AET in inches

$$AET_{\text{annual, Thornthwaite}} = 153.88\text{mm} = 6.058\text{in}$$

Table 4.12 Inputs of AET based on Thornthwaite method

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL	MEAN
P, mm	38.9	61.7	50.1	176.6	166.3	140.4	186.9	185.9	156.4	114.2	32.1	31.9	1341	
P, inch	1.5	2.4	2.0	7.0	6.5	5.5	7.4	7.3	6.2	4.5	1.3	1.3	52.8	
T, $^{\circ}$ C	19.7	20.6	20.7	20.7	20.6	20.3	17.0	17.1	17.9	18.3	20.3	19.1		19.37
T, $^{\circ}$ F	665.9	696.6	700.7	700.0	695.3	686.1	573.9	579.0	606.4	619.9	686.8	645.9		654.71

4.6.2.3.2 Formula developed by Crowe and Thornthwaite (1971)

This approach considers only the mean air temperature and applied in a specific area that satisfies the relationships presented below.

$$AET = (T-10)/9$$

Since there are many other factors that control the AET in the study area, the results obtained from these relationships are not satisfactory.

Table 4.13 AET obtained from Crowe and Thornthwaite

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
T, °F	665.9	696.6	700.7	700.0	695.3	686.1	573.9	579.0	606.4	619.9	686.8	645.9	
AET	72.9	76.3	76.7	76.7	76.1	75.1	62.7	63.2	66.3	67.8	75.2	70.7	859.6

$$AET_{\text{annual, crowe}} = 859.608\text{mm}$$

4.7 Water balance

Water balance techniques are a means of solutions of important theoretical and practical hydrological problems. On the basis of water balance approach it is possible to make a quantitative evaluation of water resources and their change under the influence of man's activities. It assists the prediction of the consequences of artificial changes in the regime of streams, lakes and groundwater basins. It is also extremely important for studies of the hydrological cycle. With water balance data it is possible to compare individual sources of water in a system, over different periods of time, and to establish the degree of their effect on variations in the water regime. Moreover, water balance studies provide an indirect evaluation of an unknown water balance component from the difference between the known components.

The water balance for any water body and any time interval in its general form may be represented by the following equation (UNESCO, 1971)

$$P + Q_{SI} + Q_{UI} - E - Q_{SO} - Q_{UO} - S - \eta = 0$$

Where P is precipitation, E is evapotranspiration, S is total water storage

Q_{SI} & Q_{UI} are surface and sub-surface water inflow in to the basin, catchement, or water body from outside

Q_{SO} & Q_{UO} are surface and sub-surface outflow from the basin, catchement, or water body

η is a discrepancy term (for all the water balance components are subjected to errors of measurement or estimation).

4.7.1 Water balance of the study area

The main objectives of balancing the hydrologic components that prevail in the study area lies in identifying the annual ground water recharge and the actual evapotranspiration of the area. In order to bring these objectives in to effect, two water balance approaches, which have generally the same ground but presented in different forms, have been applied.

The first approach follows the general water balance equation that introduces the main components that are prevailing and omits those that are of less effect in the balance. This equation is computed to obtain the annual ground water recharge of the study area.

The second approach is the one developed by Thornthwaite and Mather, 1957, known as soil water balance, and this method helps to quantify the annual actual evapotranspiration of the area on the basis of the potential evapotranspiration already computed by using empirical and physical formulae.

4.7.2 Computation of ground water recharge

Prior to making a balance among the components, defining the water balance equation to be applied in the study area followed by estimating and computing each of the components is quite crucial.

Considering the null change in ground and surface water storage in annual basis and a closed water shed boundary, the water balance equation for the study area is:

$$PPT = AET + RO + W \pm \Delta G$$

Where, PPT = mean annual precipitation in mm

AET = mean annual actual evapotranspiration in mm

ΔG = mean annual ground water recharge in mm

W = withdrawal (abstraction)

Some of the meteorological elements that are inputs for the balance have been obtained by adopting different empirical and physical approaches and are integrated to yield sound and reliable results. The remaining hydrological elements, such as surface runoff, are computed from stream hydrograph analyses in the following ways.

4.7.3 Obtaining stream flow data for Weybo River

The main Weybo River does not have a stream gauge at its mouth. An operating gauge is located at one of its tributaries upstream.

Generally two approaches have been adopted to obtain the likely discharge data of the river:

(i) Scaling up the stream flow values from the gauge to the size of the drainage area of the project stream

Scaling up is made by calculating the proportionality (Drainage-Area Ratio) between the project site drainage area and the drainage area of the gauged sub-catchment.

The estimation is made on considering the following conditions: similarity in topography, climate patterns, soil characteristics, land-use and land cover.

The discharge data at the mouth of Weybo is extrapolated from the gauging station near Areka (GPS location, 357700E, 785350N) on the basis of drainage area ratio:

$$Q_{\text{mouth}} = (A_2/A_1) Q_{\text{gauged}}$$

Where, A_1 is the drainage area of the gauging station

A_2 is total drainage area of the Weybo River catchment

Q_{gauged} is steam flow in m^3/sec of the gauged stream

Q_{mouth} is the discharge in m^3/s at the mouth of Weybo River

The monthly statistics of extrapolated flows is annexed in table-1.

(ii) Computation of stream flow by the analogue method

When selecting the analogue catchment, particular attention has been paid to similarity of the catchments' under comparison in relation to physiographic features (topography, geology, climate, soils, vegetation), morphometric features (drainage area, slope, etc) and other characteristics.

Since there is sufficient similarity between the catchments' under comparison in relation to the above characteristics, this provides a basis for transfer of discharge values from the base station to the ungauged catchment.

If normal runoff and normal precipitation at the site with a short-term observation series are Q and P , and those for the analogue are Q_{an} and P_{an} , then:

$$Q = Q_{\text{an}} (P_{\text{an}}/P)$$

The analogue catchment is, in our case, a sub-catchment of the catchment under investigation, and the analogue precipitation is obtained from the nearby meteorology stations to the sub-catchment.

The resultant flow values obtained from the above two methods are almost similar to each other and their mean values are used for further analyses.

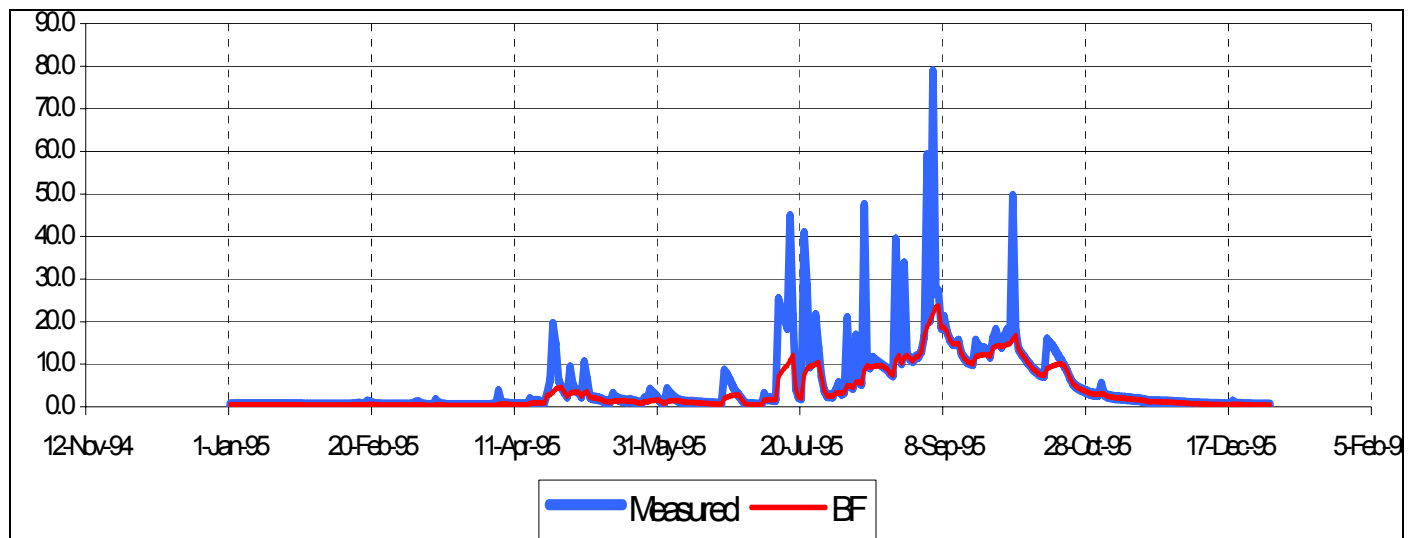
The mean monthly extrapolated flows of the catchment obtained from the above two methods are annexed.

4.7.4 Hydrograph analysis of Weybo River

The total extrapolated flow of the rivers is broadly broken down in to ground water run- off (base flow) and surface water runoff, from which the surface water runoff values are taken to equate the annual water budget of the catchment, and the hydrograph is further analyzed to obtain the annual ground water recharge.

4.7.6.1 Base flow separation

The separation of surface runoff and base flow has been made manually from extrapolated mean monthly flows and using a computer code known as Time-Plot, developed by Gabriel Parodi, which uses daily flow values and an attenuation coefficient that is controlled by the slope, land-use and land cover conditions of a water shed possessing a value in the range of 0.9-0.995. A slight difference (nearly 8%) between the resultant values has been observed and mean values are adapted for further computations.



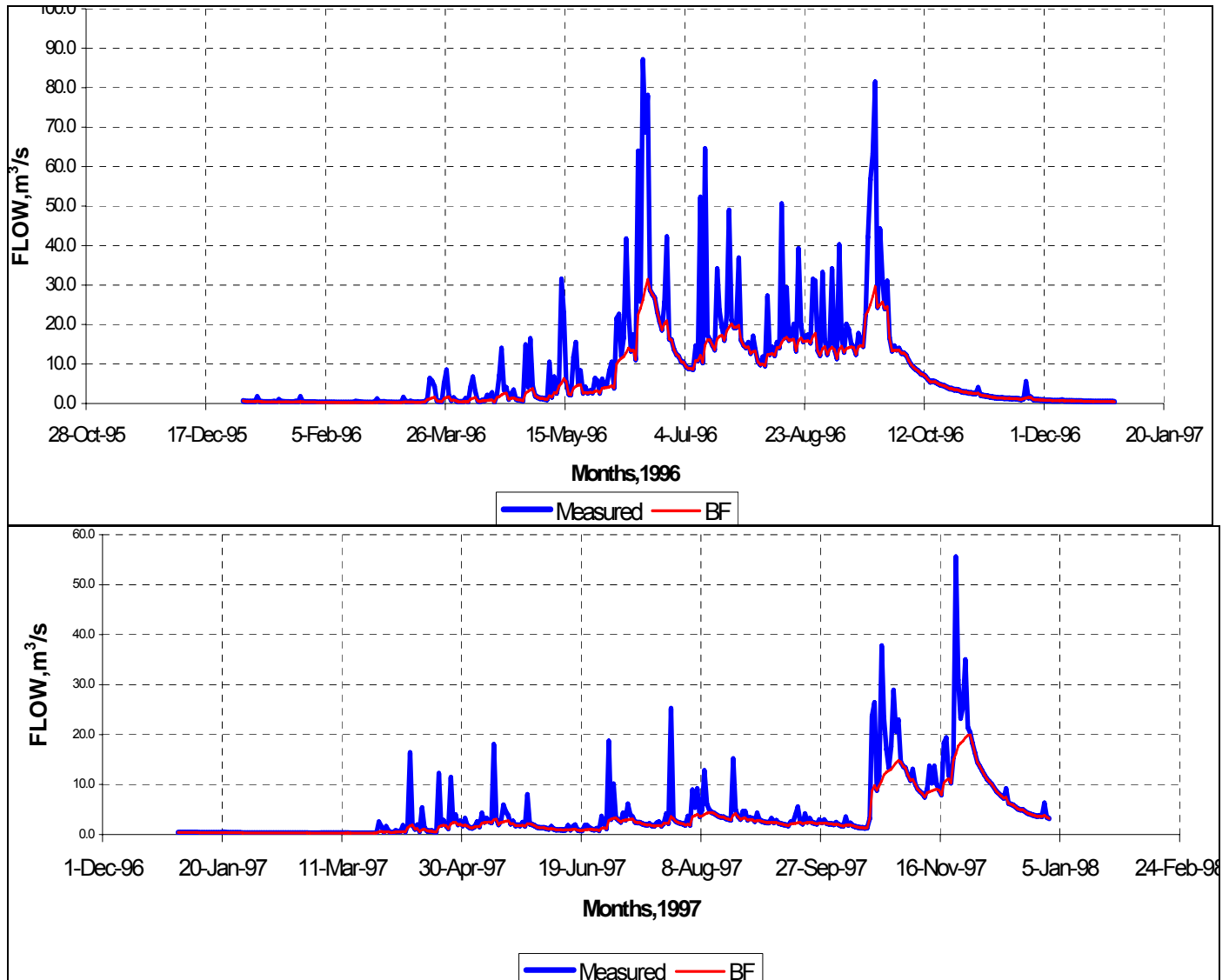


Fig 4.9 Base flow-surface runoff separations using Time-plot

4.7.5 Groundwater recharge computed from stream hydrograph

Method-1: Mean long-term base flows (mean long-term minimum flow)

Partitioning the river discharge in to direct runoff contribution from the precipitation and base flow contribution from groundwater, then the average of a 12 month total base flow and total direct runoff over a multi-year period will be the annual groundwater recharge and annual direct precipitation runoff respectively (Anderson and Woessner, 1992).

Accordingly, the mean annual base flow of the catchment (1992-2005) is calculated to be **62.5mm**.

Method-2: Seasonal recession method

This method involves in the identification of one large recession trend and one large recharge trend in a semi-logarithmic seasonal hydrograph over a 12 month period for two or more consecutive years (Meyboom, 1961).

If the exponentially decayed recession trend is plotted on a semi-logarithmic paper, it gives a straight line. The assumption is that the discharge of the stream during this large recession period below the recession trend line will be entirely due to the ground water contribution. Then, the total groundwater recharge is calculated by using the total potential groundwater discharge volume at the beginning of the recession minus the volume of potential groundwater discharge left at the end of the recession (Fetter, 1996) Based on the method,

$$V_{tp} = Q_0 t_1 / 2.3$$

Where V_{tp} = volume of the total potential groundwater discharge, m^3

Q_0 = the baseflow at the start of the recession, m^3/sec

t_1 = the time that it takes the baseflow to go from Q_0 to $0.1 \cdot Q_0$, sec

The remaining potential groundwater discharge at the end of a recession, V_t , is obtained by:

$$V_t = V_{tp} / 10^{t/t_1}$$

Where t is time length from start of recession to end of the recession

The groundwater recharge, $R = V_{tp} - V_t$

Based on this method, the groundwater recharge for consecutive 15 years is calculated (Table 4-15)

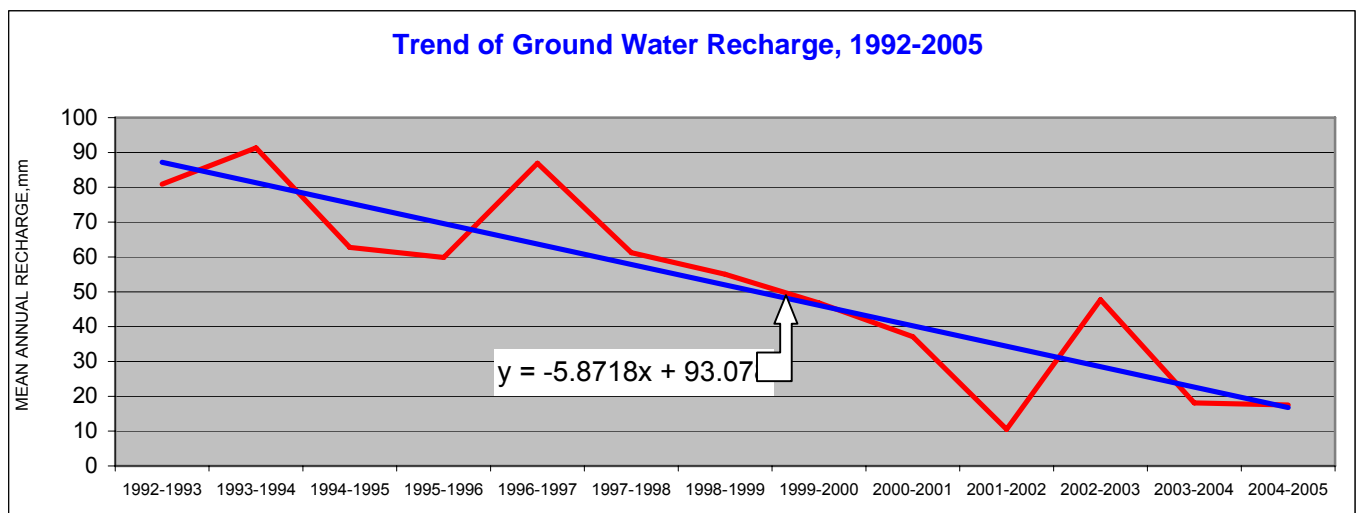


Fig. 4.10 Temporal trend of ground water recharge in the Weybo River catchment

4.7.8 Soil water balance, Thornthwaite and Mather, 1957

It has been tempted to compute the soil-water balance of the study area with the main objective of finding the actual evapotranspiration of the investigated catchment.

The approach strictly follows the one outlined by Thornthwaite and Mather, 1957.

Values of the major components of the soil water balance are presented in the following table.

Table 4.14 Soil-Water balance method of estimating AET, (Thornthwaite & Mather. 1957)

mm	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
PPT	38.94	61.66	50.12	176.55	166.25	140.38	186.92	185.9	156.42	114.16	32.12	31.93	1341
PET	68.85	114.27	106.05	132.9	89.79	71.07	54.27	60.72	80.52	76.26	112.47	107.25	1074.4
PPT-PET	-29.91	-52.61	-55.93	43.65	76.46	69.31	132.65	125.18	75.9	37.9	-80.35	-75.32	
ACC. POT.WL	-105.4	-157.9	-293.6								-80.35	-155.7	
SM	140	110	50	93.65	170.11	210	210	210	210	210	165	130	
DSM	10	-30	-60	43.65	76.46	39.89	0	0	0	0	-45	-35	
AET	48.94	91.66	110.12	132.9	89.79	71.07	54.27	60.72	80.52	76.26	77.12	66.93	960.3
D	19.91	22.61	-4.07	0	0	0	0	0	0	0	35.35	40.32	114.12
S	0	0	0	0	93.65	170.11	132.15	125.18	75.9	37.9	0	0	
TARO	17	8	4	2	93.65	216.61	240.15	245.18	197.9	136.9	68	34	
RO	9	4	2	1	47.15	108.61	120.15	122.68	99	68.9	34	17	
DETATION	8	4	2	1	46.5	108	120	122	99	68	34	17	
AWCR	210mm												

AWCR = ACCUMULATED WATER CAPACITY OF ROOT ZONE :

≈ 80% Moderately deep rooted and ≈ 20% Deep rooted plants both types grown on a Clay loam soil

From Table developed by Thornthwaite and Mather, 1957, the total Available Water Capacity of the Root zone (AWCR) for both types of land covers grown on clay loam soil is calculated to be ⇒

80% (200mm) + 20% (250mm) = 210mm

TARO = Total available for runoff,

PPT = Mean Monthly Precipitation, mm

PET = Potential Evapotranspiration, mm

AET = Actual Evapotranspiration, mm

Acc. POT.WL = Accumulated Potential Water Loss, mm

SM = Soil Moisture, mm

DSM = Change in Soil Moisture, mm

D = Soil Moisture Deficit, mm

S = Soil Moisture Surplus, mm

RO = Run Off, mm

Descriptions and estimation/computation approaches of each of the main components that basically influence the balance is presented in the following way.

The mean monthly precipitation (P) values obtained from Thiesen polygon method is presented in raw 1 of the table.

The mean potential evapotranspiration calculated by the Penman and pan evaporation methods is listed in row 2.

Changes in the balance of the precipitation and meteorologic demand of each month is computed and presented in row 3, following the computation, the accumulated potential water loss which is obtained by adding meteorologic demands (the negative values of P-PET) of consecutive months are listed in row 4.

The available water capacity of the soil is obtained from a table developed by Thornthwaite and Mather, 1957. The table gives, for an 80% coverage of moderately deep rooted crops grown on a clay loam soil having a rooting depth of 0.8m and for the remaining 20% coverage of deep rooted crops grown on a clay loam soil texture with a rooting depth of 1m, an available water capacity of root zone of 210mm.

Using the graph, water retained in the soil against an accumulated potential water loss, and the available water capacity for the soil, the amount of water that will be retained by the soil (soil moisture, SM) for each month is calculated and listed in row 5.

The change in the soil moisture during the month is obtained by deducting the soil moisture of the month under consideration from the soil moisture of the preceding month. These values are entered in row 6.

The actual evapotranspiration equals the potential rate during the months when the precipitation exceeds potential evapotranspiration this is because the rain water is considered to be easily available to the plant even if the soil moisture of the whole root zone is not raised to the available water capacity. At times when the potential evapotranspiration exceeds the precipitation amount the actual evapotranspiration will be equal to the sum of precipitation and the amount of soil moisture withdrawn from storage.

The soil moisture deficit is calculated easily by subtracting the actual evapotranspiration from the potential. The moisture surplus (amount of water that can not be stored), which is attained after the soil moisture reaches its field capacity, is obtained by subtracting the change in soil moisture from values of (P-PET).

The total amount of water available for run off is simply equal to the amount of soil moisture surplus for the first month, but its value for the superceding months could be obtained by adding

the surplus of the month and the detained amount of water in the preceding month because this detained water is thought to be readily available for run off for the coming month. These values are listed in row 10 of table.

Based on the bold assumptions of Thornthwaite and Mather, 1957, 50% of the surplus water that is available for run off in any month actually runs off, the rest 50% of the surplus is detained in the subsoil, groundwater and channels of the catchment and is available for runoff during the next month.

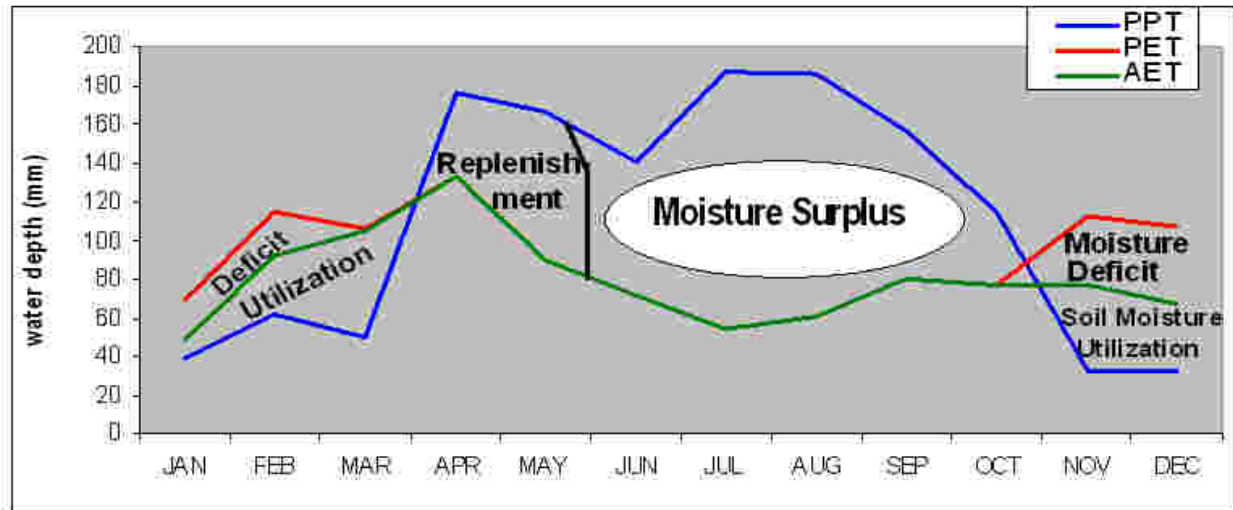


Fig.4.11 Annual water balance of the study area

Applying the general water balance equation set for the catchment, the annual ground water recharge is then estimated as follows,

$$PPT = AET + SRO \pm \Delta G + W$$

$$\Rightarrow \Delta G = PPT - AET - SRO - W$$

$$\Rightarrow \Delta G = 1341\text{mm} - 960.3\text{mm} - 291.7\text{mm} - 0.81\text{mm}$$

$$\Rightarrow \Delta G = 88.19\text{mm/annum}$$

4.8 Assessment of the ground water recharge conditions

4.8.1 The optimum and reasonable amount of ground water recharge

Four different recharge values that are significantly differ from each other are obtained by adopting four different approaches, including the chloride mass balance. The optimum and reasonable values are selected by evaluating the ground water budget of the catchment. In accordance with this, the mean value of recharge obtained from the conventional water balance approach and the base flow recession methods show a reasonable correlation with the

groundwater budget. And it is concluded that the mean ground water recharge of the study area is about 81.5mm/year.

Table 4.15 Ground water recharge obtained from mean minimum flow (MMF), seasonal recession method, and conventional water balance approach

Water Year	Recharge-Base flow (MMF), mm	Recharge Seasonal Recession Method, mm	Recharge from water balance
1992-1993	80.8800	69.3791	
1993-1994	91.3180	62.3117	
1994-1995	62.7480	87.7429	
1995-1996	59.8360	158.2974	
1996-1997	86.9310	64.9742	
1997-1998	61.2130	82.0905	
1998-1999	55.0470	71.4562	
1999-2000	46.8020	64.8691	
2000-2001	37.1030	113.4073	
2001-2002	10.5000	26.5452	
2002-2003	47.7350	81.0657	
2003-2004	18.0850	40.0902	
2004-2005	17.4840	46.9473	
Mean	62.9610	74.5521	88.190

4.8.2 Trend, relationships with controlling hydro-meteorological parameters and fate of groundwater recharge

It has been observed that the ground water recharge is progressively declining in appreciable rate. The decline in the rate of recharge has been treated by analyzing the temporal trending patterns of some of the hydrometeorologic elements that have a good relationship with groundwater recharge conditions. Trends of these elements are presented in the following way,

- Mean precipitation is slightly decreasing, however, its rate of declination is not comparable with the significant decrease in ground water recharge
- The annual surface runoff of the catchment is increasing
- The mean minimum temperature shows an increasing trend
- The mean wind speed shows an increasing trend
- The potential evapotranspiration is slightly increasing

It could be said, at this juncture, that the changes in these hydro-meteorological factors are mainly a function of the changes in the environment, in general.

The declining straight-line equation of ground water recharge indicates that the fate of ground water reserve will be heavily affected and appreciable change in storage will be seen after 30 years now on.

5. Hydrogeology

5.1 General

The principal hydrogeologic properties of rocks are porosity, effective porosity or specific yield, and permeability. These properties control the entrance of water in the water-bearing formations or rock, their capacity to hold, transmit and deliver water, and confinement and concentration of percolation to the direction of maximum ease of movement.

Hydrogeologic properties depend chiefly on porosity, size of openings or interstices and their shape, arrangement, interconnection, and continuity. Rock formations and the openings there in are the results of primary geologic processes which form the rocks and secondary processes that modify them, either increasing or decreasing their porosity and permeability. The occurrence of water in the rocks of any region is therefore determined by the character, distribution, and structure of the rocks it contains.

Volcanic rocks predominantly cover the study area. These rocks exhibit greater variations in their water bearing properties. Basic volcanic rocks like basalts are generally rich in cavities (formed due to high mobility lava flowing for more time and space before solidifying and thus escaping lot of gasses) and contraction cracks; and as such, may become permeable and sources of underground water (S.G. Garg, 1983). On the other hand, acidic volcanic rocks may or may not contain ground water although generally they possess interstices. The reason is that the interstices may be filled up with ash and other material, and hence uncertainty. Pyroclastic rocks associated with lava flow are generally porous. However, their permeability varies depending on the interconnection of the pore spaces (Davis et al, 1966).

Openings in volcanic rocks include gas cavities, porous flow textures & structures, openings between included rock fragments, and interstices in tuffs & breccias. Fractures are the principal openings in such rock types. Large fractures, usually few in number, are produced by deep-seated earth stresses and may extend to great depth; and small near- surface fractures may occur in great numbers (Nockolds, Knox, Chinner, 1979).

5.2 Hydrogeologic units and aquifer systems

The main hydrogeologic units in the study area are extrusive volcanics that are subjected to varying degrees of secondary activities, especially to weathering. Fracturing and local faulting are also among the activities that act on the rock units in some portions of the area.

Due to their mode of genesis and emplacement, the majority of the units lack primary structures, mainly porosity & permeability, however, those pyroclastic ejectas outcropped in the area possess an appreciable primary porosity. Secondary processes play a significant role in the localization and controlling of the ground water systems of the catchment. These hard facts are evidenced by the lithological logs of boreholes drilled within and in the surroundings of the catchment. Around 20 boreholes to a maximum depth of 182m and a minimum of 55 m below ground surface have been bored in and very near to the study area. The major water bearing formations in all of the bores are weathered and fractured ignimbrites, sediments associated with unwedded tuff and trachytes and rhyolites. The weathered column thickness of the units, as inferred from geophysical survey results and aquifer thickness of the boreholes, are mainly dictated by three/four conditions

- 1) In areas where the aquifer units are overlain by the pyroclastic tephra (pumices and volcanic ashes), the thickness of the weathered column is higher and varies from 24 m to 36 m
- 2) In the recharging areas of the catchment, thickness gets thinner and thinner (boreholes drilled at Kerenso & Kotu localities)
- 3) Boreholes drilled at the banks of streams possess a relatively thicker aquifer column at shallower depths
- 4) Weathered thicknesses of the units that are overlain by alluvial sediments are also observed to possess a relatively thicker column.

From pumping test analysis and lithological log maps of the bore wells in the area and its nearby vicinities, yield of the wells is not linearly correlated to the thickness of the weathered column. Moreover, in most of the wells, moderately weathered units are preferred to the deeply weathered units and the wells that are screen cased in the moderately weathered portion yield better than those that are screen cased adjacent to the deeply weathered portions. This could be attributed to the reduction in the effective porosity of the aquifer material by the deeply weathered products of the formation.

5.2.1 Aquifer formation, type, thickness, depth and lateral extent

Three different aquifer formations are identified in the study area on the basis of the type of the parent material, and material mode of emplacement, the welded tuff unit (ignimbrite) being known to cover wider portion of the study area.

In some of the boreholes, three of the aquifer formations exist with varying thickness and at a variable depth. The spatial distribution mapping of the formation is basically made considering the dominant formation that is encountered at depth as inferred from well logs and from the surface geology of the area, i.e. the lateral extension of the formations is made on the basis of:

- i) Hydrostratigraphic correlations of the formations, and
- ii) Surficial extensions of the formation's parent material as inferred from the surface geological map of the study area.

5.2.1.1 Weathered and fractured ignimbrite/welded tuff

This unit is the major aquifer formation in the eastern, central and south-eastern portions of the study area.

It outcrops at a depth variably from 8m below ground surface in the central part to 14 m in the east and south-east part of the catchment and overlying in some parts on a slightly weathered welded tuff and at others on rhyolites and basalts; and overlain in most parts by slightly to deeply weathered pumaceous deposits and alluvium, and some parts by rhyolites and trachytes.

As inferred from the hydrostratigraphy of the area, this formation is continuous in the sub-surface across the catchment except in the western and north-north-western zones of the area. It extends beyond the north-east and south-east boundary of the catchment in to the Sokie, Ajora and Bilate catchments. In the extreme south of the study area, around Sorfella plain, this formation is relatively unexplored for the reasons that boreholes and their lithological logs are basically non-existent. However, it has been inferred from the hydrostratigraphy of the area and geophysical surveys conducted at the plain, that the formation (moderately weathered part of the formation) could be encountered at a depth range of 30-40m.

5.2.1.2 Sediments associated with weathered pumice

This formation widely covers almost the entire area of the catchment, however, it is thinner and sometimes missing in the recharging area and it gets thicker and thicker in the central & north-west parts of the catchment. The formation immediately overlies slightly to moderately weathered ignimbrite and rhyolites in most parts. Thick sediments are outcropped at a shallower depth especially at the banks of streams that drain the central portion of the study area and at the foot of south-eastern ridges. This formation is the main source of groundwater in the central and partly north-west parts of the study area, where over 50 hand dug wells are bored that tap water mainly from this aquifer formation. This formation is thought to receive a direct recharge from precipitation which is evidenced by the seasonal fluctuation in the water level of the wells during dry and wet seasons. Some of them dry up during dry season and water levels decline in most of the wells.

5.2.1.3 Weathered and fractured rhyolites and Trachytes

These units are the third most to widely form the aquifer system of the study area. Boreholes that tap water from this aquifer formation (those drilled around Kerenso (Badewacho), Lera (Konteb), yield 1.5 to 12 l/sec where as those that tap water from the weathered and fractured welded tuffs yield 2 to 14 l/sec. Weathered and fractured rhyolite and trachyte formations are majorly outcropped at a variable depth of 10m–130m around the north-western and south-western portions of the study area. The weathering degree is observed to decrease down depth as inferred from borehole logs drilled at the north–north–east part of the area. The formation overlies its fresh parent through out the area which intern overlies fresh, slightly jointed basalt at the north-west tip of the study area & the welded tuff in the west and south-west parts of the catchment; and it is overlain by ignimbrite in most parts and by pumice and unwelded tuffs in some part of the study area.

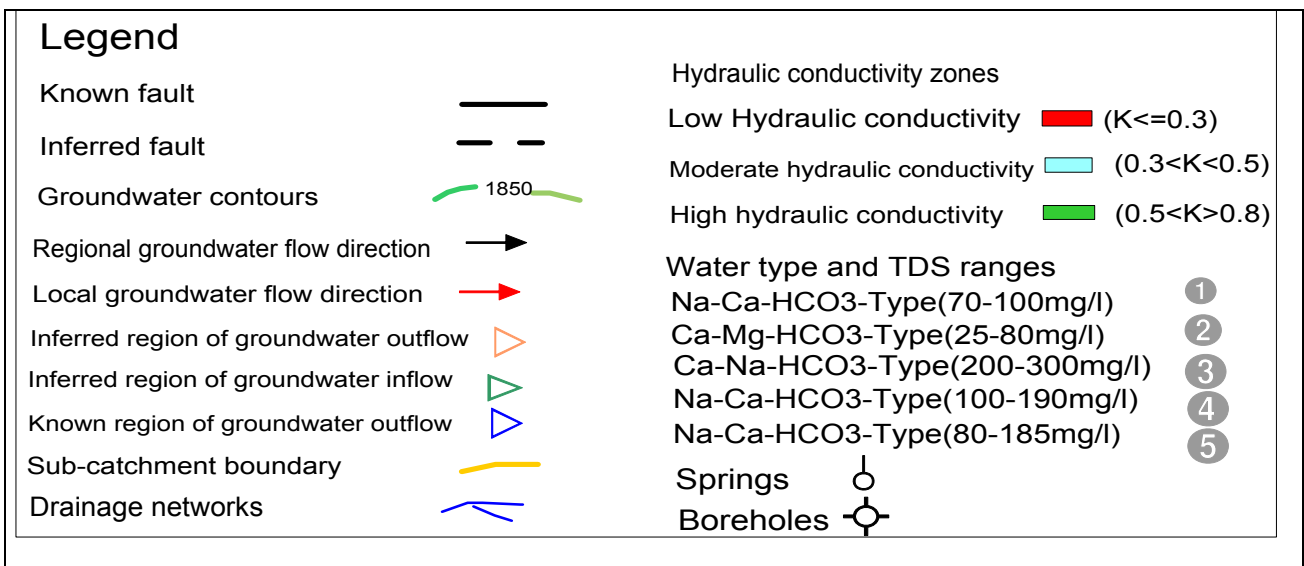
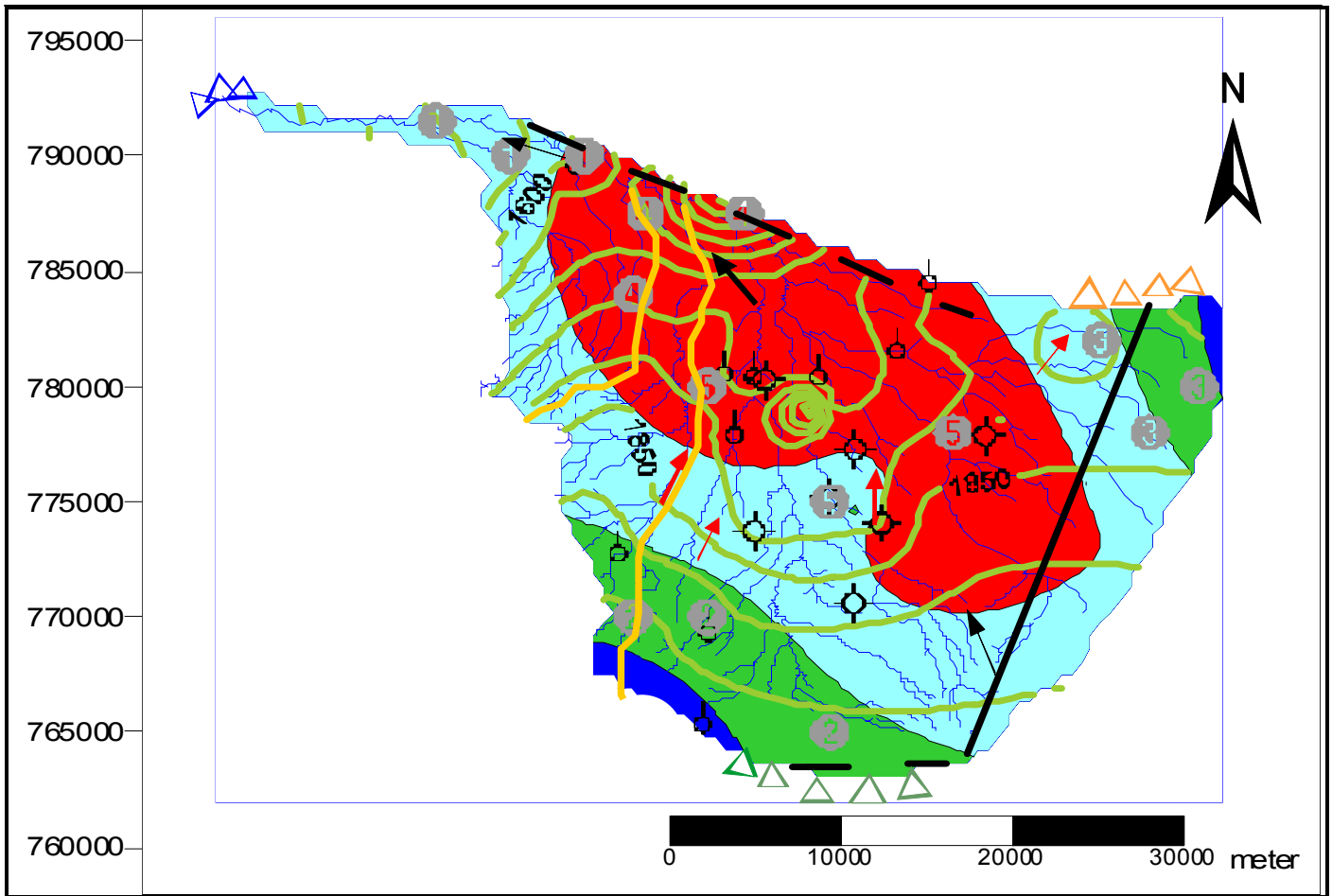


Fig. 5.1 Hydrogeological map of the study area

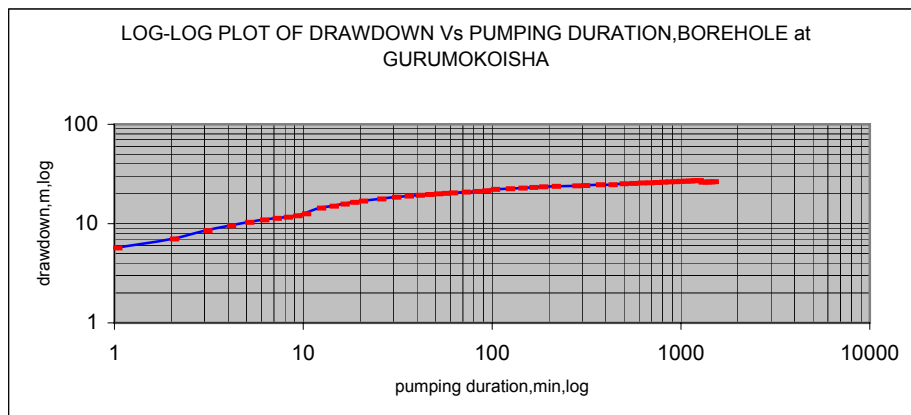
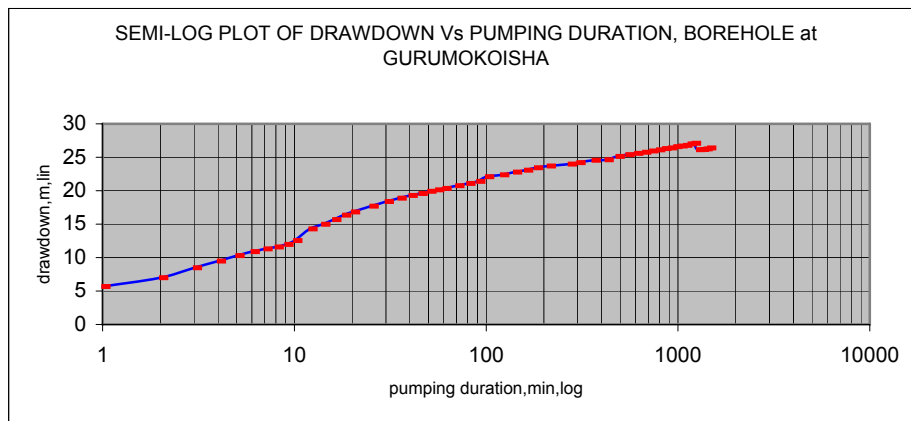
5.2.1.4 Types of aquifers in the catchment

Confined, leaky and unconfined aquifers in the catchment

Aquifer types (confined, leaky, unconfined) of the area have been distinguished in two/three ways. The first approach utilizes pumping test records and plotting of the discharge against time on logarithmic and semi-logarithmic-scaled papers.

The plots help identify the system that is strictly rely on models, the characteristics of which are assumed to represent the characteristics of the real aquifer system i.e. identification of the aquifer system is made by comparing its draw down behavior with that of the various theoretical models. This aquifer system identification involves the constructions of diagnostic plots (log-log plots of the draw down versus the time since pumping started) and specialized plots (semi-log plots of draw down versus time) the resulting characteristic shapes of the curves help in selecting the appropriate model.

In our case, the semi log plots of draw down versus time have more diagnostic value than log-log plots; but both types of graphs have been constructed to facilitate the system identification.



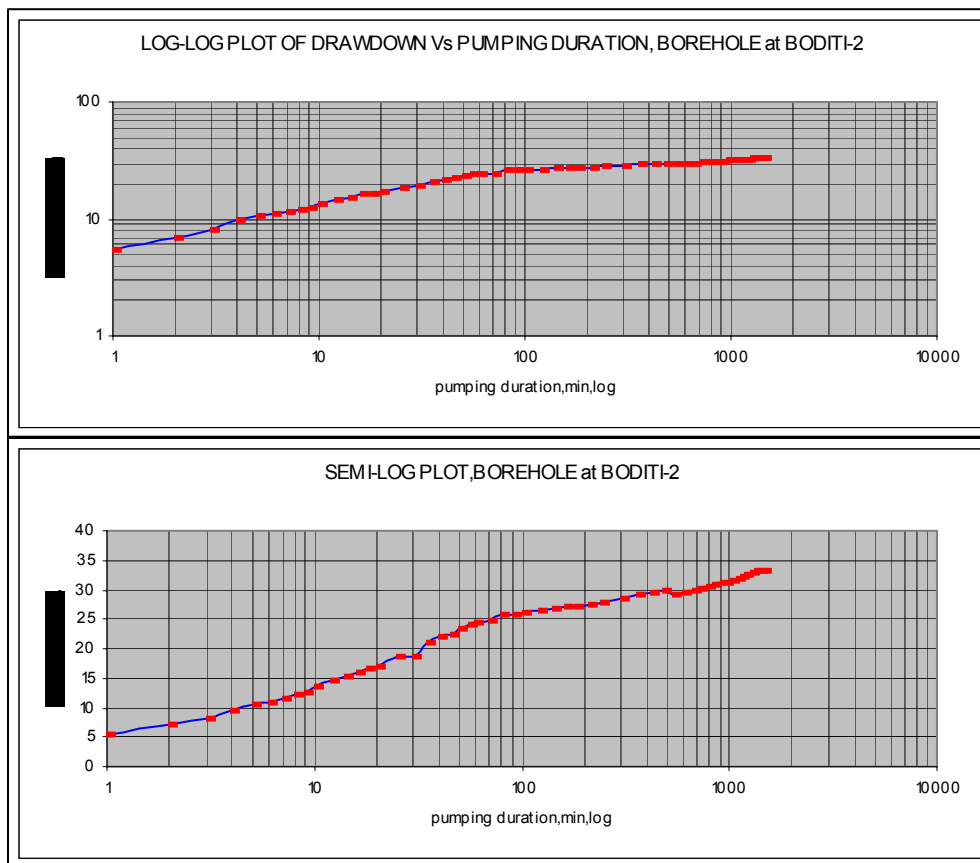


Fig. 5.2 Diagnostic and specialized plots for some representative boreholes

Analyses and comparison of the plots with the theoretical models reveal the existence of leaky and confined aquifers in the study area. From the plots, most of the boreholes pump water from leaky aquifers (Look at the diagnostic & specialized plots and theoretical models).

The other approach relies on analysis of lithological logs of hand-dug wells & machine drill bore wells that are more or less distributed evenly within the catchment. Logs of some wells, situated very near to the study area and lie in the same hydrogeologic set-up are also adapted. The litho-log analysis is supported by the general geological set up of the study area and its adjacent catchments. Most of the boreholes have been seen to possess aquitards as a confining layer.

The third approach, which is applied in conjunction with the second one, is observation of the seasonal fluctuation of dug wells and springs. The fluctuation is thought to arise in response to seasonal changes of surficial processes that have direct connection with the aquifer. Recharge to these aquifers is thought to come from downward seepage through the unsaturated zone. This is evidenced by seasonal fluctuations in the levels of the water table during wet and dry periods.

In some of the areas where there is a proper well completion record, (shallow and deep wells drilled by UNICEF emergency program, 2002, around Gununo) interpretation on the first depth of the main aquifer struck and the final level that the water rests after completion of the drilling process (i.e. the static water level) gives a clue on the aquifer type.

Based on the analyses discussed earlier, three of the aquifer types are explored in the study area. The unconfined (water table) aquifers are extensively crop out in the central and eastern parts of the catchment to a depth range of 6-13m below the ground surface. These aquifers are overlain by a slightly to moderately weathered, thin, pumaceous deposits and sediments. Leaky aquifers are the most to form the aquifer system of the study area. Most of them are crop out at a depth range of 20m with a confining aquitards majorly of slightly weathered ignimbrite and red-brown silty clay soil. The confined types are also found at a depth, in mot cases starting from 30m below ground surface.

5.3 Hydraulic characteristics

About 13 boreholes are available in and very near to the study area that are equipped with submersible electrical pumps; out of which 11 boreholes possess pumping test and proper well completion reports which were compiled by the Southern Region Water Works Construction Enterprise, SABA Engineering Private Limited company and the Southern Region Water Resources Development Bureau.

Out of the 11 boreholes, only 2 are equipped with an observation pipe of diameter $\frac{3}{4}$ ".

5.3.1 Pumping test type and duration

All boreholes are pumped at a constant pumping rate for a duration of 24 hours, and discharge rate and draw down measurements are made on the pumping wells. Piezometer nests (and/or monitoring wells) are absent in and around the study area; and water level measurements of nearby wells (existing wells drilled for community use) were not considered in the schedule of the pumping process. The absence of Piezometer and failures in considering existing, nearby functioning water wells in the schedule of the work limits the possibility of deducing the effects of local hydraulic conditions in and near the pumping well such as measurements of storage coefficient that strongly influence the draw down in the well and interpret the aquifer system of the area under influence.

In almost all the tests, steady state or equilibrium is reached and data analysis is made using a suitable well-flow equations developed for such a condition. Most of the analyses were made using the formula developed by Cooper and Jacob, 1946.

5.3.2 Hydraulic conductivity

Hydraulic conductivity is governed by the size and shape of the pores, the effectiveness of the interconnection between pores, and the physical properties of the fluid. If the interconnecting tubes are small, the volume of water passing from pore to pore is restricted and the resulting hydraulic conductivity is quite low. The hydraulic conductivity indicates the quantities of water that will flow through a unit cross-sectional area of a porous medium per unit time under a hydraulic gradient of 1.

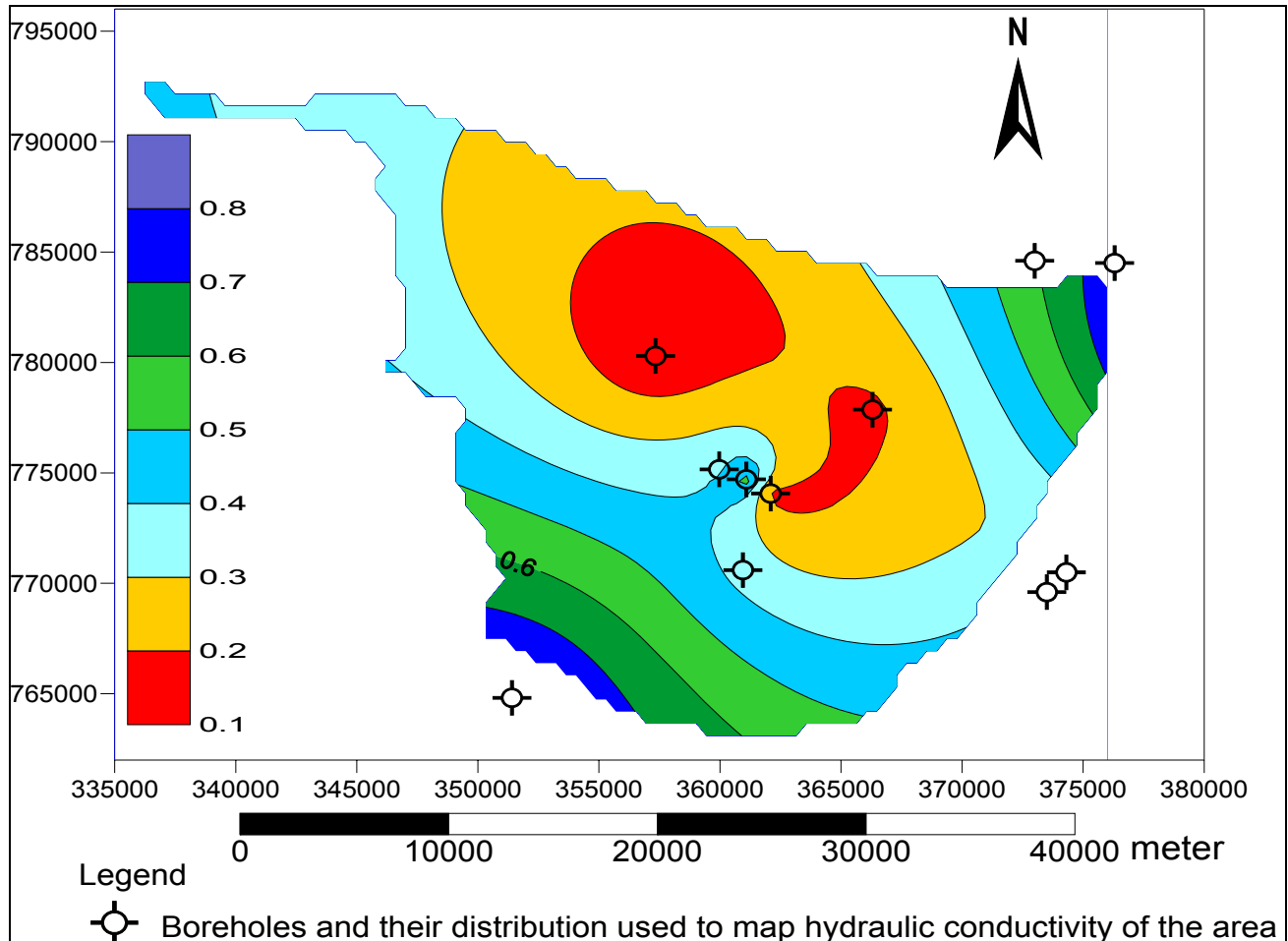


Fig. 5.3 Hydraulic conductivity map of the study area.

Some degree of correlation could be made between the geological structures and the distribution of the hydraulic conductivity values.

The area around the extreme north-east of the catchment, where there is an inferred N-E to S-W running fault (look at the geological map of the study area) and all along that line and its vicinities, the hydraulic conductivity values are distinctively rising; whereas, the central parts of the catchment, where there is a relatively thick weathered column, the conductivity values are decreasing and are in the range of 0.175m/day to 0.55m/day. It, then, could be said that, for such a hydrogeologic environment, secondary structures (faulting and fracturing) play a paramount role than weathering. This analysis comes in agreement with the one made by Stanley N. Davis and Roger J.M. Dewiest, 1966. According to these authors, both the hydraulic conductivity and porosity of volcanic rocks tend to decrease slowly with geologic time. Some of this decrease is owing to compaction, but the filling of pores with secondary minerals and weathering products is probably the most important cause of the decrease.

Since the upper part of the rhyolite flow and ignimbrite bed are weathered to a range of moderate to deep extent, a reduction in the size of fractures and other openings occur, with a consequent progressive decreasing of the permeability of the complex rock bodies.

In conclusion, it is possible to say that a greater extent of the study area possesses a low permeability unit.

Some of the hydraulic parameters of the aquifers obtained from pumping test analyses are annexed in table 3.

5.4 Ground water flow systems and potentiometric surfaces

5.4.1 Regional, intermediate and local flow systems

Water that enters the flow system in a given recharge area may be discharged in the nearest topographic low or it may be transmitted to the regional discharge area in the bottom of the major valley (Toth, 1966).

Local, intermediate and regional flow systems of groundwater flow of the study area have been differentiated in three/four ways.

i) Waters that are discharged from areas of relatively flat topographic set-up, especially those high yielding and perennial springs (Tadisa-Bara, Mere, Gamowalana, Chena, Gidhomba and Tulame springs), the flow system is considered to be regional for the fact that the areas where the springs are emanating are not basically recharging zones and are relatively far from topographic highs, and the local relief there is not pronounced.

ii) Shallow depth and perennial dug wells that are bored on a relatively flat topography are also thought to be crossed by regional flow systems.

iii) Intermittent and low yielding springs and dug wells are considered to be crossed by either local or intermediate flow systems for they are recharged from nearby areas that is susceptible to surfacial phenomena. These water sources are majorly concentrated in topographic highs and serves the community during rainy season and immediately before the on-set of dry months.

iv) The in-situ measurements of the electrical conductivity values (and/or total dissolved solids (TDS measurements) give a good picture in differentiating the three ground water flow systems (This is treated in the hydrochemistry chapter of this paper).

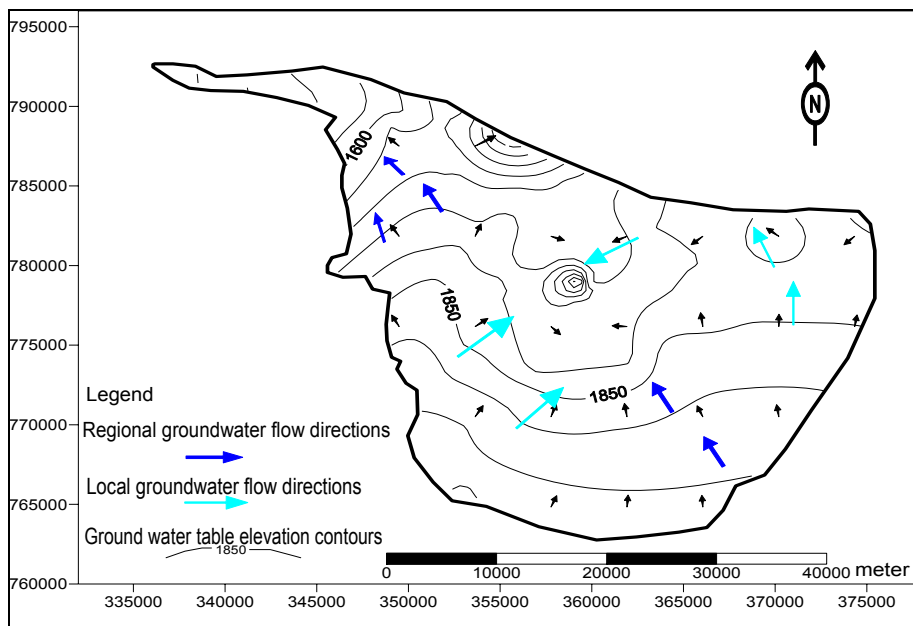


Fig. 5.4 Regional and local groundwater flow systems shown on a potentiometric surface map

5.5 Recharge and discharge zones

According to Myboom, 1966a and Toth, 1966, there are five basic types of indicators of recharge and discharge areas which include, topography, peizometric patterns, hydro chemical trends, environmental isotopes, and soil and land surface feature. Among these indicators, topography is the simplest (Freeze and Cherry, 1979) and peizometric measurements are the most direct.

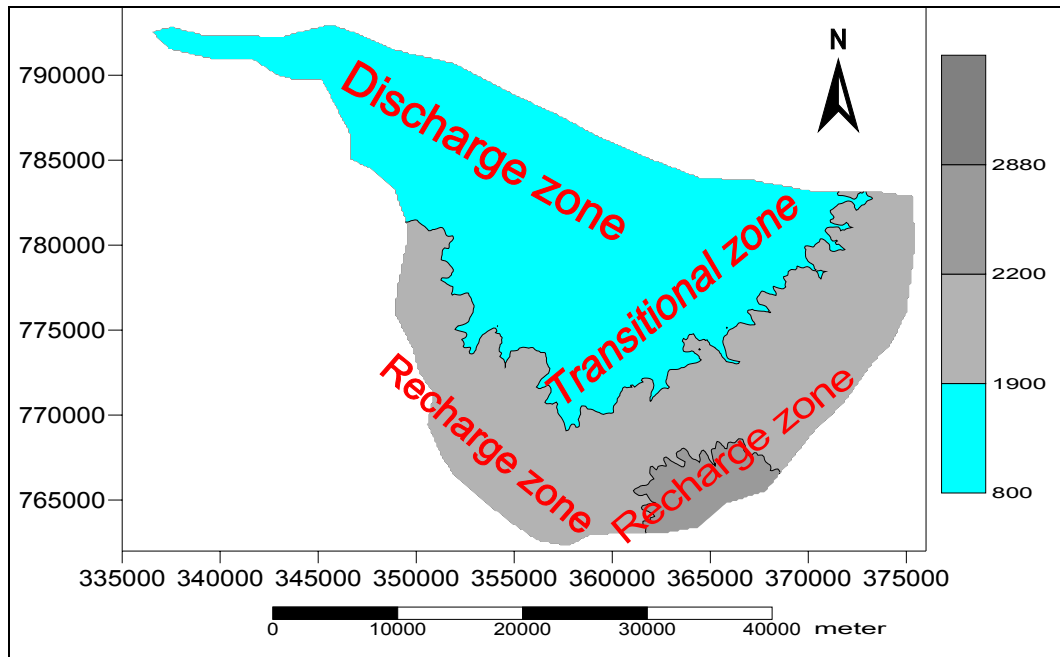


Fig. 5.5 Recharge and discharge zones in inferred from elevation contours

The water table contour map helps to locate ground water recharge and discharge areas. The flow vector lines (fig. 5.7) tend to diverge from recharge areas and converge toward discharge areas. The convergence of the vector lines is clearly seen in the north-west and central parts of the study area, and the divergence of the flow lines is observed in the southern, south-eastern, south-western and north-eastern parts of the catchment.

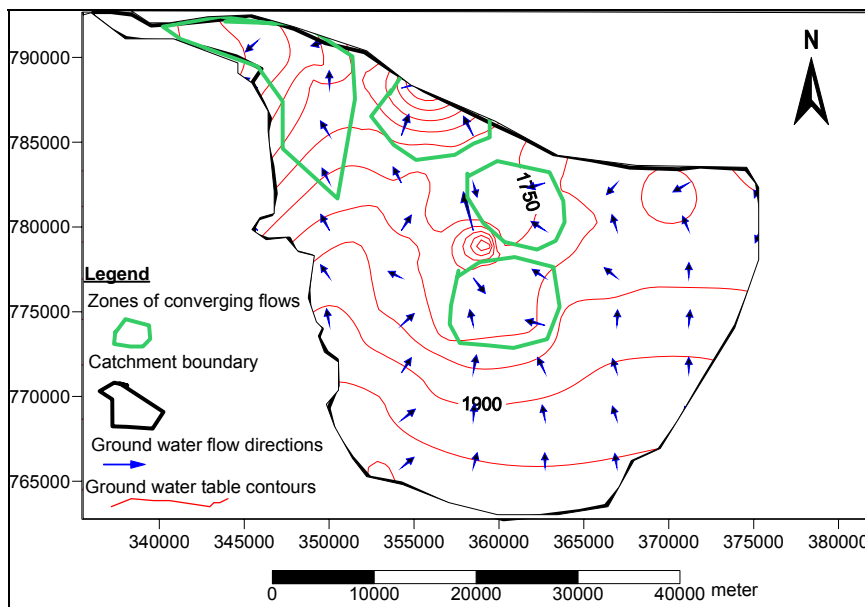


Fig. 5.6 Convergence and divergence zones of flow lines showing recharge and discharge zones.

In general, ground water discharge from the Weybo aquifer system occurs as spring discharge, flow to the tributaries and the main Weybo River, and directly evapotranspire in the wetland areas of Lei-Tedisa and Sukie. However, ground water discharge by evapotranspiration from the Weybo aquifer system is considered to be insignificant compared to spring discharge because most of the aquifers are deeply seated below land surface. Moreover, these areas are very small compared to the areal extent of Weybo aquifer system.

5.6 Ground water divides

Ground water divides are imaginary and vertical impermeable boundaries across which there is no flow (Freeze and cherry, 1979).

Within the study area, mapping of the ground water table contours help to identify ground water divides. The flow directions that are controlled by the hydraulic heads indicated by arrows dictate the dividing lines. The first divide is clearly mapped at the western part of the catchment that runs from right south to north starting from the geographic location of 350000E, 764000N.

The other divide is mapped in the eastern part of the area running south to north-north-east starting from a point of 373000E, 764000N.

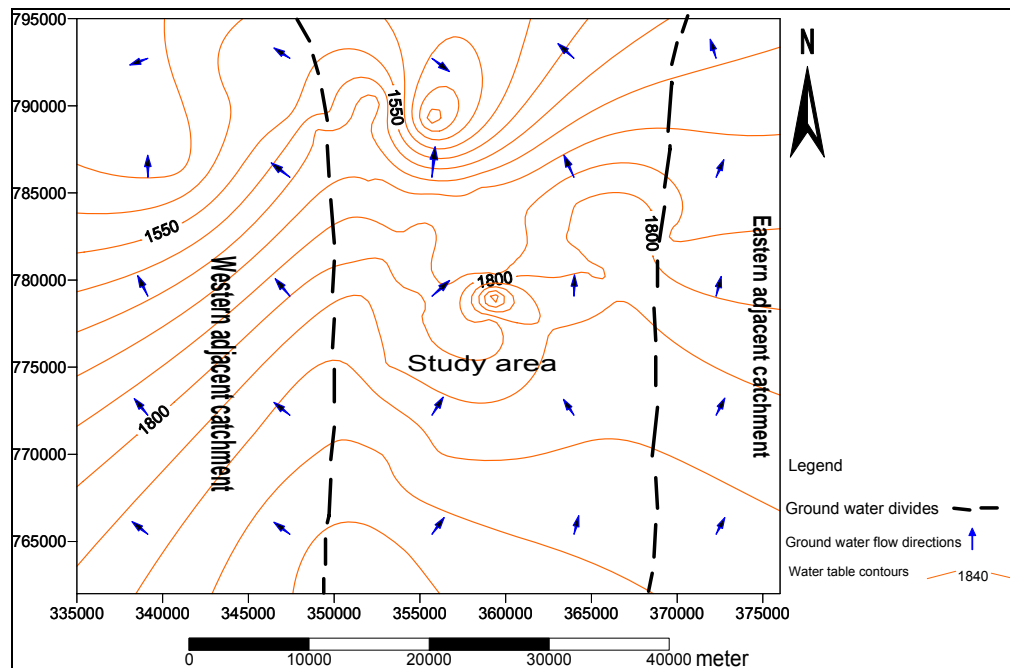


Fig. 5.7 Ground water divides locations inferred from flow vectors

It has been interpreted and analysed from the surface morphology and the groundwater level contour map that the surface water divide in the eastern boundary overlaps in a more or less perfect manner with the ground water divide. Where as, the surface water and ground water divides show a very slight offset in the western boundary of the catchment and it could be possible to conclude that the surface and ground water divides are coincident and the system could be considered as symmetric in these two boundary zones. Moreover, this is evidenced by the flow directions of both surface and ground waters in that the surface water and ground water flow lines coincides to each other in the anticipated locations of the ground water divides (look at Fig. 5.8)

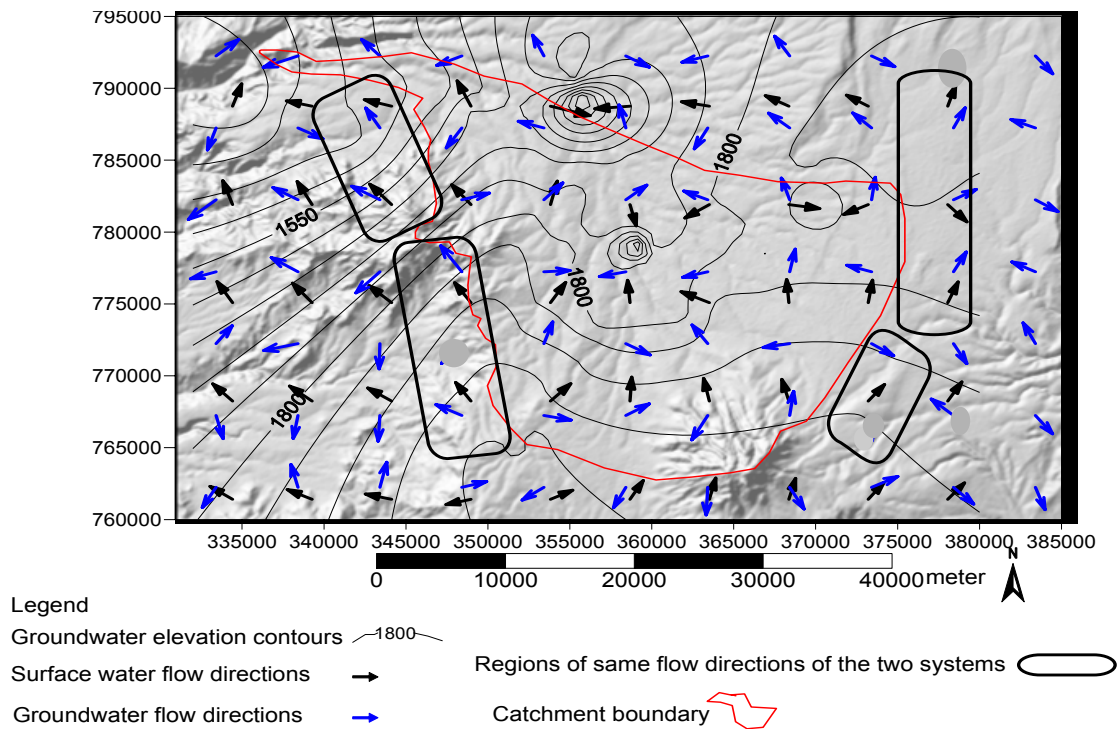


Fig. 5.8 Surface and ground water flow directions

Due to lack of hydraulic head data in the northern and southern neighboring watersheds, the overall symmetry of the systems is not proved.

5.7 Groundwater-surface water interactions in the Weybo river catchment

Ground water and surface water are not isolated components of the hydrologic system, but instead interact in a variety of physiographic and climatic landscapes (Sophocleous, 2002). In many regions ground water and surface water resources are connected, and most surface water features (rivers, lakes, dams, wetlands) generally interact with groundwater. The exploitation of, or quality of one resource, can therefore affect the other.

Since there are no monitored data of groundwater level changes and stream discharge rates, ground water extraction data for production bores, piezometer transects (flow nets) and bore and stream hydrographs, in the area under investigation, the interaction of surface water and ground water in the study area is analysed using the basic principle and relationship that guide ground water and surface water interaction. The principle is stated in the following way.

Rivers generally interact with groundwater in three basic ways (Winter et.al., 1998) - streams gain water from inflow of groundwater through the stream bed (gaining stream), they loss water to ground water by outflow through the stream bed (losing stream), or they do both, gaining in some reaches and losing in other reaches. For ground water to discharge in to a stream channel, the elevation of the groundwater surface in the vicinity of the stream must be higher than the elevation of the river stage. Conversely, for surface water to seep to ground water, the altitude of the water table in the vicinity of the stream must be lower than the elevation of the stream-water surface.

Interactions of the two systems are evidenced by observations of flow vector directions of the ground water table contours overlapped with the drainage networks (look at fig. 5.10).

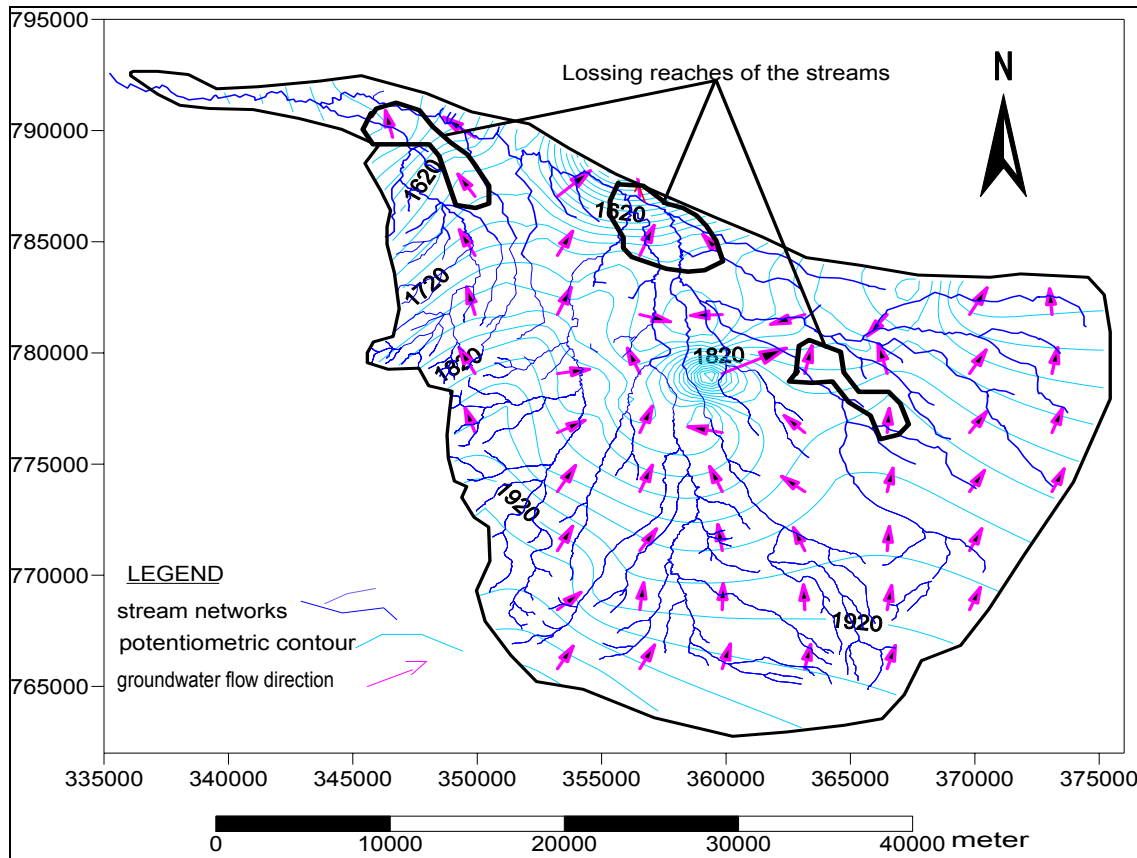


Fig. 5.9 Effluent and Influent streams showing surface and ground water interactions

Most parts of the streams are gaining water from the ground water system. However, some parts of the streams in the lower and partially central zones of the catchment loose water to the sub-surface system. This has also been confirmed by comparing the ground water table elevation and the elevations of the streams beds.

Table 5.1 Groundwater table elevations and streambeds elevations at some selected reaches

Measurement Location		Stream bed elevation (m.a.s.l.)	Groundwater table elevation (m.a.s.l.)
E	N		
361000	773000	1860	1856
366500	776000	1874	1883
363500	779000	1855	1846
362000	780000	1780	1777
354000	772000	1920	1918
356500	785900	1590	1599
356500	787000	1560	1564

5.8 Available groundwater sources inventory and hydraulic characteristics

5.8.1 Hand dug wells

Around 42 hand-dug wells have been inventoried during the prefeasibility study phase of the program. All are located within the study area; some are fitted with Afrideve hand pumps while abstractions in the majority of the dug wells are carried out by pulley system. Some of the dug wells have served for over 15 years with only slight changes in their yields; still construction of new dug wells is under progress. Depths of the dug wells vary from 9-29m while the majority of the wells lie at a depth range of 10-20m with variable static water levels of 3m - 27m. The most frequently measured static water level of the wells ranges from 7-13m below the ground surface. In many of the sites, the unsaturated soil formation is a red-brown silt clay associated with slightly to moderately weathered pumice, possessing a variable thickness of 3-18m, being thinner in the eastern and south-western recharging zones.

The major aquifer formation is known to be moderately weathered and fractured ignimbrites (in the central and eastern parts) and alluvial deposits in the northern, north-western and partially central parts of the catchment. Moderately weathered and locally fractured rhyolites and trachytes are the formations in the western and south-western portions of the study area.

Most of the dug wells provide a perennial source of water, however, yield is substantially decreasing during dry season there by tapping of the wells made during morning and night times. The seasonal fluctuation of the static water levels in most of the wells is highly attributed to the direct recharge condition from precipitation in to the well which intern indicates the unconfined nature of the aquifers. Most of the dug wells are constructed in the discharging zones and central parts of the study area and at the banks of both intermittent and perennial streams.

5.8.2 Boreholes

Both deep and shallow boreholes are drilled in the study area by different charity organizations and the government. There are about 18 deep and 2 shallow boreholes. Deeper boreholes are those that possess a depth beyond 60m, and all that have a depth below 60m are considered shallow. The deepest borehole has a depth of 182m drilled at a locality known by the name Dengera Selata. 11 of the deeper boreholes are fitted with submersible electrical pumps and the remaining deep and shallow boreholes are equipped with Indian mark II, III, and Afrideve hand pumps and wind-powered pumps.

The main aquifer formations of the boreholes are weathered and fractured ignimbrite, alluvium, weathered and fractured rhyolites and trachytes having a variable thickness and variable weathering and fracturing intensity. The static water level of the wells lies within the range of 14m-80m with a frequent level ranging from 30m-60m below ground surface. Aquifer thickness, hydraulic conductivity and yield of the aquifers lie between 18-36m thick, 0.1 - 0.875m/d, and 1.4-8l/sec respectively.

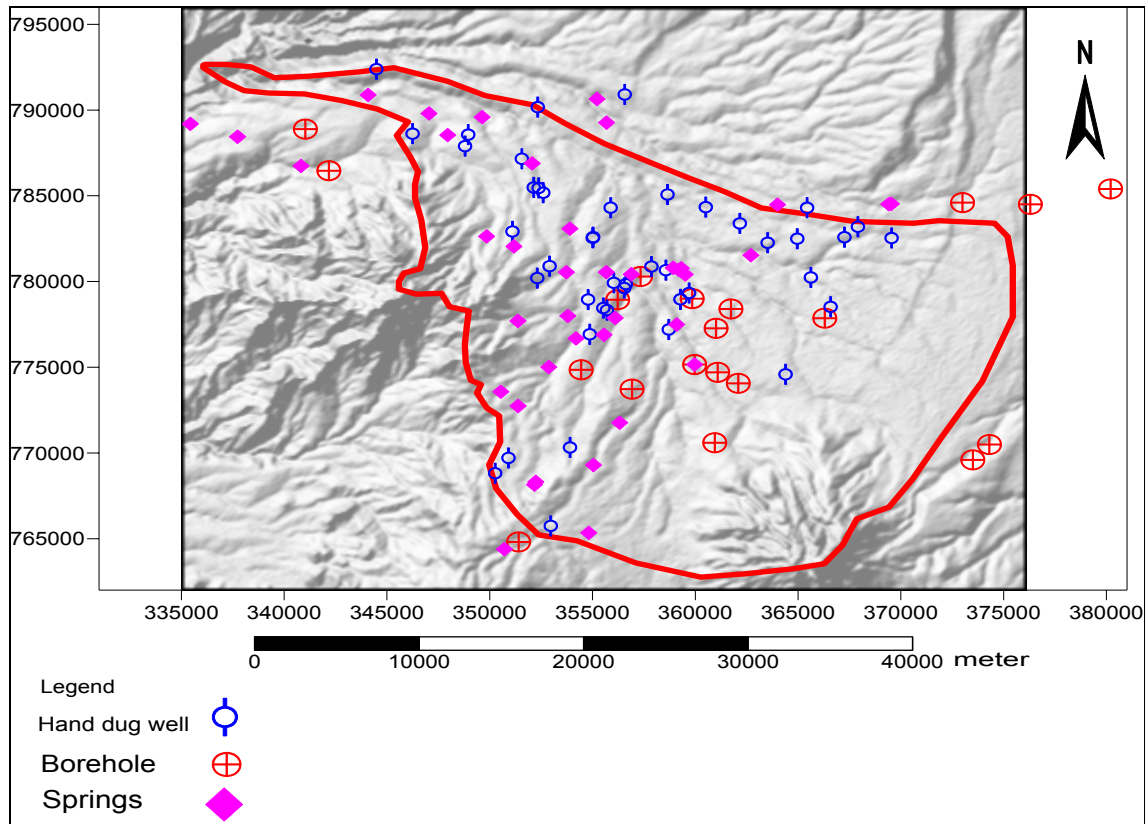


Fig. 5.10 Distribution and locations of shallow and deep boreholes, hand dug wells and springs in and near the study area.

Inventory data of groundwater sources are annexed in table 4.

5.8.3 Springs

About 25 springs have been inventoried in the study area, most of them are poorly protected, some are developed in a good condition, and still others are not constructed yet.

Many of the springs (almost all) are discharging water through out the year, even during dry seasons; however, their yield highly fluctuates with seasons. As inferred from the field measurements in wet and extreme dry seasons of the investigation period, and an interview made with the local community members and the district's water resources development department personnels, four of the springs discharge water in a more or less constant (with insignificant fluctuation) rate.

The springs are depression and contact type, where most of them are emanating from banks of depressions and topographic lows; still some are structure controlled in that their emanating zones are affected by fracturing.

The discharge variability of the springs have been measured by applying the formula developed by Meinzer (Davis and Dewiest, 1966):

$$V_a = [(Q_{\max} - Q_{\min}) / Q_{\text{md}}] * 100$$

where: V_a is the percentage of variability, Q_{\max} is the maximum discharge

Q_{\min} is the minimum discharge, Q_{md} is the median discharge

Accordingly, the springs are classified as constant springs when $V_a < 25\%$, sub-variable springs when $25\% < V_a < 100\%$ and variable springs when $V_a > 100\%$.

Based on the variability percentage and the magnitude of discharge rate, two of them are Meinzer's approach to classify springs, the springs in the study area are classified using the wet and dry seasons discharge data value measured during the investigation periods.

Table 5.2 Spring types and class (Classification based on Meinzer's method)

	Name of Spring	GPS-Location			Discharge		Va (%)	Classification-1 (variability)	Classification-2 (magnitude)	Spring Type
		E	N	Elevation	Dry season	Wet Season				
1	Mere	355047	769297	1907	4	4.8	18.18	Constant	5th	Depression
2	Tekacha	350715	764395	2025	0.18	0.234	26.09	Subvariable	6th	Depression
3	Watere	353901	783084	1738	0.07	0.098	33.33	Subvariable	6th	Contact
4	Tilike	349852	782634	1760	0.04	0.056	33.33	Subvariable	7th	Contact
5	Ocashe	351180	782050	1763	1.6	2.08	26.09	Subvariable	5th	Contact
6	Hitie	364000	784480	1798	0.064	0.089	32.68	Subvariable	6th	Contact
7	Mun-Awa	354196	776681	1810	0.04	0.06	40.00	Subvariable	7th	Structure
8	Tulame	351378	772741	1910	2	2.6	26.09	Subvariable	5th	Contact
9	Kaei	350541	773576	1939	0.5	0.65	26.09	Subvariable	6th	Contact
10	Chena	340823	786738	1429	4	4.8	18.18	Constant	5th	Depression
11	Adilla	347050	789803	1523	0.4	0.52	26.09	Subvariable	6th	Structure
12	Ajora	344576	793051	1451	1	1.3	26.09	Subvariable	5th	Structure
13	Bara	359510	780410	1719	36	38	5.41	Constant	3rd	Depression
14	Tedisa	359195	780685	1728	10	12	18.18	Constant	4th	Depression
15	Kule-Areka	356889	780427	1731	0.4	0.52	26.09	Subvariable	6th	Depression
18	Marana	355675	780544	1750	0.29	0.377	26.09	Subvariable	6th	Structure
19	Gidohomba	349633	789586	1595	2.5	2.8	11.32	Constant	5th	Depression
20	Wadu	362708	781536	1761	0.6	0.75	22.22	Constant	5th	Depression
21	Weybo	353800	778000	1800	0.1	0.14	33.33	Subvariable	6th	Structure
22	Achura	355219	790644	1761	0.2	0.28	33.33	Subvariable	6th	Structure
23	Dubo	353730	780545	1781	0.07	0.09	25.00	Subvariable	6th	Structure
24	Weybo	352872	775011	1851	0.01	0.014	33.33	Subvariable	6th	Structure
25	Tedisa-Lei	358926	780800	1716	0.05	0.07	33.33	Subvariable	6th	Structure
26	Gidohomba	352066	786887	1691	0.01	0.014	33.33	Subvariable	6th	Structure
27	Weybo	355563	776593	1795	0.05	0.07	33.33	Subvariable	6th	Structure

5.9 Ground water budget of Weybo river catchment

A control volume is defined for the aquifer system of the catchment prior to computing the balance of the ground water components.

The control volume of interest is the layered aquifer system that comprises both the leaky, confined and unconfined conditions, and that takes in to account negligible or no under flow, negligible or no evapotranspiration from the system, and no recharge from other catchments.

The basic form of any groundwater budget equation is given by:

$$\Sigma(\text{Inflows}) - \Sigma(\text{Outflows}) - \Delta\text{Storage} = 0$$

$\Sigma(\text{Inflows})$ is the summation of inflow components in to the control volume expressed as a volume of water per unit time

$\Sigma(\text{Outflows})$ is the summation of outflow components out of the control volume

ΔS , the change in storage, is the net gain or loss of water from the control volume resulting from changes in the inflow or outflow components.

5.9.1 Steady state condition

The rate of change in storage in the ground water budget is negligible for an aquifer in steady-state condition because the assumption is made that inflows and outflows are in balance.

In the case of the study area, and for the purposes of this analysis, the groundwater budget equation is expressed as:

$$\Sigma(\text{Inflows}) - \Sigma(\text{Outflows}) = 0.$$

5.9.2 Groundwater budget components

As illustrated in the above equation, the ground water budget consists of both inflow (recharge) and outflow (discharge) components.

Discharge components are estimated for the known physical boundaries of the groundwater flow system (the control volume) of the aquifer in the study area.

Most outflows from the aquifer occur as surface discharge (comprised of discharge of stream as baseflow and discharge to springs). Abstraction (pumping) of water from the aquifer to human

and animal consumptions is considered but very small and ground water pumping to irrigation canals is absent.

The base flow outflow component is estimated from extrapolated flow data as discussed in the chapter of hydrology.

The spring discharge, i.e. the outflow component that does not contribute to stream flow and therefore, is not measured at a stream flow-gauging station is thought to be recharged back or evapotranspired or consumed. During rainy seasons, evapotranspiration from these springs are almost negligible and some percent of water (say 50%) is consumed and the remaining is thought to be recharged back to the aquifer; where as during dry seasons almost all flow will either be consumed or evapotranspired with negligible back recharge. Therefore, the amount of water from these springs (i.e. from low yielding springs that their flow don't reach to flow gauging station) is partitioned in to two – the amount which is recharged back, and amount which is added to the out flow component (by evapotranspiration during dry seasons and consumption in all seasons).

In the Weybo river catchment, the total spring discharge at the source is 1.87×10^6 m³/year. This value is computed by simply summing the discharge of known springs in the record. From this measured amount of spring discharge, about 1.57×10^6 m³/year (especially contributed from Tedisa-Bara, & Wadu springs) are thought to be measured at the stream flow gauging station located at one of the tributaries of the main Weybo river. Other unmeasured springs exist, but flow from these sources is considered negligible compared to flow from the known measured sources.

The remaining 2.931×10^5 m³/year is not measured at the gauging site. Break down of this lump sum (the amount that is not measured at the gauging site) is made on the basis of the above description.

The total aquifer discharge is, there fore, about 43056100 m³/year including discharge to streams as base flow and to springs.

Downward leakage to the underlying basaltic formation (deeper than 300m) and other water bearing units that exist probably below 250m is considered to receive recharges from the upper main aquifer units of Weybo river catchment. Because of the physical boundaries of the ground water system (the control volume, in our case) it is assumed that all discharge from the deeper

formations is leakage from the upper and main aquifer formations of Weybo river catchment since no outcrops of these deeper formations are exposed to intercept precipitations.

The evapotranspiration component from the ground water system (control volume) is the amount of water lost to the atmosphere by evaporation from the water table and transpiration by plants that withdraw water from the saturated zone. Even after summing these two terms, the amount of water lost to evapotranspiration is negligible; therefore the evapotranspiration term is dropped from the outflow components.

Abstraction (discharge) of water from the aquifers for human and animal consumptions is simply computed by multiplying the average abstraction rate from all the boreholes dug wells and springs within the catchment by the days in the year and the length of pumping duration. About 462527 m³/year of water is estimated to be withdrawn from the aquifer, and discharge of water from the aquifers to irrigation canals is considered zero as there are no irrigation fields that are watered by pumping aquifers. Therefore total outflow from the Weybo aquifer system is the sum of the base flows, spring discharges that their discharge is not measured at the stream-flow gauging site but is partly consumed and partly evapotranspired and total annual abstraction from boreholes and hand dug wells. And their sum yields 43056100 m³/year.

Table 5.3 Summary of the Ground water Budget Components

A	B	C	D
Average annual recharge (as estimated from water balance and base flow recession methods) (mm/year)	Mean annual abstraction rate (estimated by simple arithmetic computation of discharge rates from pumping boreholes and hand-dug wells) (mm/year)	Mean annual base flow (estimated from hydrograph separation) (mm/year)	Mean annual aquifer discharge to springs that is not recorded at the stream flow gauging station (mm/year)
81.5mm (43250900m ² /year)	0.81 mm/year (462527m ³ /year)	74.5 mm/Year (42763000m ³ /year)	0.511 mm/Year (293100m ³ /year)

5.9.3 Balance

Under steady state conditions, discharge from the aquifer is assumed to be equal to the total recharge to the aquifer.

However, Mean annual recharge(A) \neq Mean annual abstraction(B) + Mean annual baseflow(C) + Mean annual discharge to springs that is either evapotranspired or consumed(D)

$$81.5 \neq 78.561$$

When this mathematical statement, (A=B+C+D), is further elaborated, the maximum amount of outflow from the aquifer, given a steady state condition and an aquifer that is bounded from bottom and sides by an impermeable layer to avoid bottom leakage and lateral exchange of water with aquifers of adjacent catchments, equals to the amount that the aquifer receives.

Nevertheless, in the case of the catchment under investigation, the inflow amount exceeds that of the outflow (see the above inequality equation). This condition could be justified in the following three or four ways provided that one of the justifications outweighs over the others for the effect of the one will change the certainty of the other:

- i) There may exist underpass of water either at the flow gauging site or some where along the streams channel
- ii) There will be migration of ground water from the catchment to neighboring catchments at structural conduits.
- iii) The base flow - surface runoff separation might be doubtful since it is subjective
- iv) The recharge rate computed from either base flow recession method or water balance method is doubtful.

6. Hydrochemistry

6.1 General

Advances in hydrochemical methods and approaches have aided our ability to interpret hydrochemical processes in ground water systems, and improved understanding of how structural, geological, mineralogical, and hydrological features affect flow and chemistry in these systems.

Hydrochemical information can be used to interpret the origin and mode of ground water recharge, refine estimates of time scales of recharge and groundwater flow, decipher reactive processes, provide paleo-hydrological information, and calibrate ground water flow models.

Hydrochemistry can assist in understanding the evolution of water chemistry (quality), to examine natural base line conditions against which human impacts can be recognized and to take a look at some ways in which the protection and management of groundwater resources can be achieved. Some information on key minor and trace elements (Fe, Mn and F, for example) is also a requirement for understanding the geochemical environment, as well as, for potability assessment.

6.2 Objectives and approach

It has been tempted to quantify the amount and rate of recharge, delineate recharge and discharge zones, identify regional, local and intermediate flow systems, and qualitatively assess the relative importance of geologic factors in controlling the chemistry of the water in the study area.

The objectives have been achieved through methods that are widely in use today. These approaches follow some sorts of procedures designed prior to conducting the field and laboratory works. Sampling sites and their sources are mapped in a view to avoid redundant and similar sampling there by to obtain contrasting information. Measurements of the main in-situ parameters that dually help in cross-checking the validity of the laboratory results (to some extent) and in understanding the geochemical environ has been carried out using pH-meter and EC-meter (both of them are HANNA products), well calibrated in the laboratory with proper calibration reagents. Measurements of major, minor and trace elements have been made in the regional laboratory (Southern Region Water Resources Bureau) using three different measuring systems. Some of the major cations (such as Ca, K, an Mg), anions (such as SO_4^- , PO_4^- , F^- ,

Br^- , NO_3^-) and minor ions (such as Fe, Mn, Cu, Co) have been measured by an electro- photo spectrometer that injects light in to a solution that is well conditioned by proper amount and type of reagents and immediately tells the absorbed amount of light in terms of concentration of that specific element. The remaining anions (HCO_3^- , CO_3^{2-} and Cl^-) are measured by titration processes, and Na^+ is computed by making an overall balance between the cations and anions. Seasonal sampling has also been made in wet and dry months in order to observe concentration changes of chloride.

Presentation of the results in a variety of ways (Piper, Collins, and Schoeller) and classifying them using statistical means (Hierarchical cluster analysis, HCA) has been made to facilitate the interpretation and analyses. Then all the samples of the study area were statistically examined. Trend and concentration analyses have been made by mapping a number of variables separately, such as EC (TDS), pH, Eh, Cl^- , Na^+ , Ca^{2+} and Mg^{2+} that greatly help interpret flow paths, recharging and discharging zones, local, intermediate and regional flow systems in the study area.

6.3 Sampling sites and method

The distributions of springs, boreholes and hand-dug wells have been examined in a view to identify reference areas, to give a representative geographical and hydrogeological sample distribution. These reference areas consisted of a total of 34 samples all from recharging, discharging and adjacent catchments and one from rain.

The method involves the withdrawal of water from pumping boreholes and hand dug wells and tapping the non-stored free flowing springs followed by measuring of pH, Eh, EC, TDS and T. The samples are contained by a polyethylene green colored plastic bottle that partially prevent the entrance of solar radiation (the green paint partially prevents the entrance of solar rays to some degree but not able to fully avoid the penetration of the ray) and were reached to the laboratory within 15 days and laboratory measurements are then carried out.

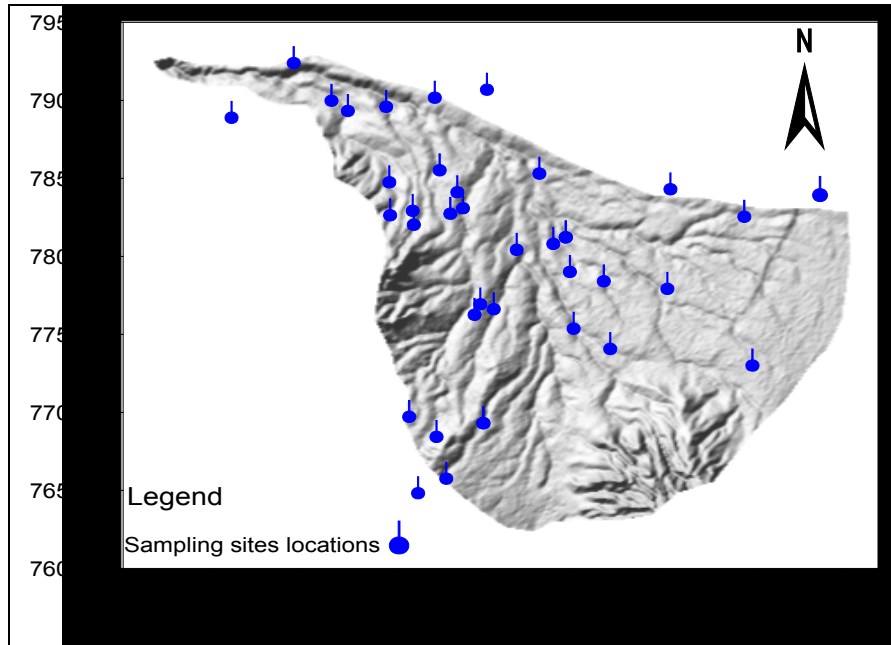


Fig. 6.1 Sampling sites location

Examination of the different sources of water in the field is an important part of hydrologic study. Certain properties of water, especially the pH, are so closely related to the environment of the water that they are likely to be altered by sampling and storage, and a meaning full value can be obtained only in the field.

6.4.1 pH (hydrogen ion activity)

The hydrogen ion activity is controlled by inter-related chemical reactions that produce or consume hydrogen ions and the geomeidia. Biochemical processes are also among the factors that control the pH-levels of natural waters. Most ground waters found in the study area have pH values ranging from about 6 to 7.5. The pH levels of each of the water sources tend to increase toward north and north-west parts of the study area that are the discharging zones.

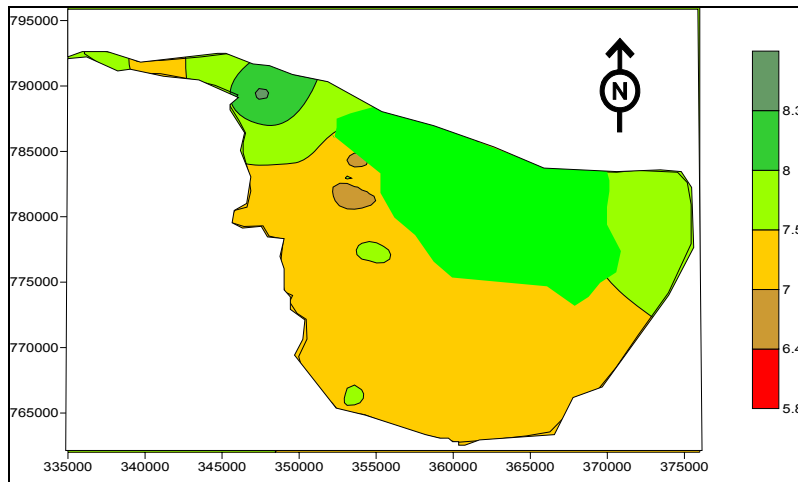


Fig. 6.2 Trend of pH in the area

There is some difference between the average pH values of springs, dug wells and boreholes (see table below).

Table 6.1 pH differences among different sources of water

Source	pH max-locations			pH min-locations			Number of samples = X, Y, Z			
	E	N	Elevation	E	N	Elevation	X, pH <6	Y, 7.5>pH>6	Z, pH>7.5	Total no. of samples
BH	346590	789976	1543	350715	764395	2025	1	17	2	20
				353901	783084	1738				
SP	340823	786738	1429	364000	784480	1798	5	20	9	34
	347050	789803	1523	355675	780544	1750				
				352872	775011	1851				
				352335	790170	1686				
HDW	356568	790910	1707	343328	789296	1547	2	20	-	22
	348972	788111	1667	349339	764649	2110				
				348436	768737	2123				

Source	Maximum	Minimum	Average
BH	8.2	5.71	6.85
SP	8.36	5.62	6.87
HDW	7.2	5.9	6.33

6.4.2 Electrical conductivity (EC)

Electrical conductivity of water is its ability to conduct an electric current at a specified temperature (Weast, 1968). The presence of charged ionic species in solution makes the solution conductive. As ion concentrations increase, conductance of the solution increases; therefore, the conductance measurement provides an indication of ion concentration.

It is apparent that the relationship between electrical conductivity and ionic concentration of water is direct, and most of the data set fit a straight-line regression closely (correlation coefficient= 0.6).

Electrical conductivity values show significant variations with the different sources of water. It has been observed that most of deep boreholes have a higher EC values and these values are progressively decreasing for shallow source of water.

Table 6.2 Electrical conductivity values for the different sources

	Maximum	Minimum	Average
BH	410	57.8	227.56
SP	380	50.6	161.68
HDW	362	47	138.44

A 2-dimensional contour plot of the EC values reveal an increase in the EC values in the central and north-north-west parts of the study area.

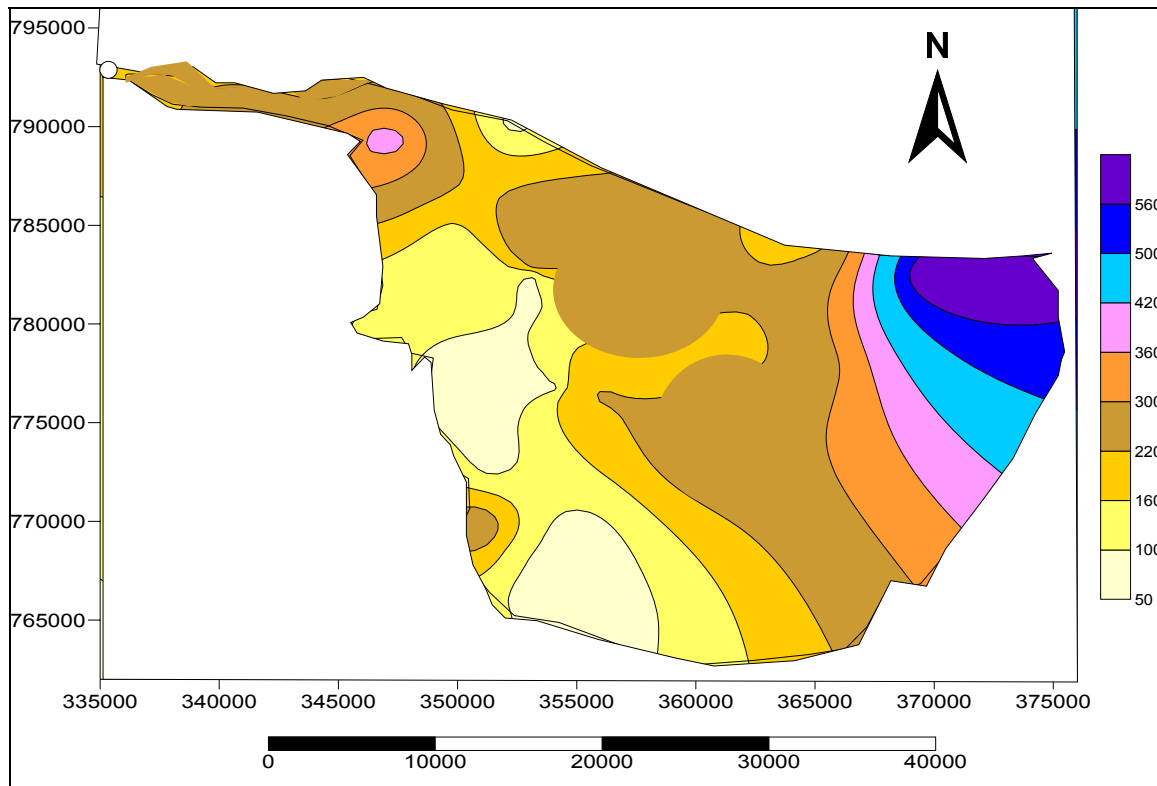


Fig. 6.3 Electrical conductivity map

It could be seen from the map that EC values are getting higher and higher towards the discharging zones and their values are generally lower in the recharging zones-around South-West and South.

6.4.3 Redox potential (Eh)

For chemical reactions in which electrons are transferred from ion to another (redox reactions), the oxidation potential of an aqueous solution is called the Eh (Drever, et.al. 1997).

High Eh is generally the direct result of dissolved oxygen in the water.

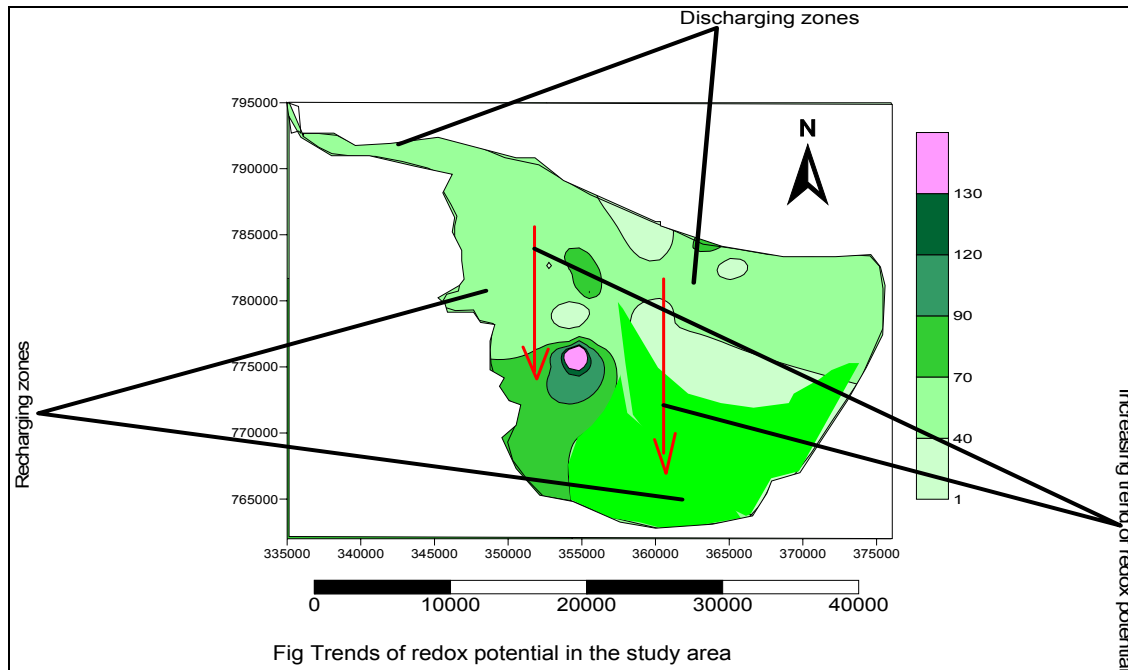


Fig 6.4 Trends of redox potential in the study area

As observed from the surface map of Eh, it is sufficiently low for the north-north-west parts, and its value gets higher near the recharging zones (around south-west and south) due to the fact that the ground water may have sufficient dissolved oxygen to elevate the Eh. In general, the highest oxidation potentials are in shallow ground water of recharge areas and it is found to decrease with increasing length of flow towards the discharging area (Look at surface map of Eh). This is mainly attributed to the fact that as the water travels through the aquifer, the oxygen is chemically reduced by contact with reducing species resulting in the lowering of Eh.

6.5 Classification and presentation of laboratory measured parameters

The spatial variability observed in the composition of the major ions (as natural tracers) can provide insight in to aquifer heterogeneity and connectivity as well as the physical and chemical processes controlling water chemistry. Generally the approach is to divide the samples in to hydrochemical groups (facies or clusters), that is group of samples with similar chemical characteristics that can then be correlated with location. Verification that systematic variations along the flow path are related to reactions between ground water and the aquifer provides the hydrochemical evolution trend for the study area. This information provides the context for interpreting the spatial variations in water chemistry and defining ground water flow paths and characterization of the hydrologic systems.

It is tempting to use some of the many available graphical and statistical methodologies to classify the water samples including Piper diagram, Collins bar, Schoeller plot, and Q-mode hierarchical cluster analysis (HCA).

6.5.1 Graphical presentations

Most of the graphical methods are designed to simultaneously represent the total dissolved solid concentration and the relative proportions of certain major ionic species (Hem, 1989) and all the graphical methods use a limited number of parameters, usually the available data, unlike the statistical methods that can utilize all the available parameters.

Piper diagram

The diagram displays the relative concentrations of the major cations and anions on two separate tri-linear plots, together with a central diamond plot where the points from the two tri-linear plots are projected. The central diamond-shaped field (quadrilateral field) is used to show overall chemical character of the water (Hill, 1940; Piper, 1944).

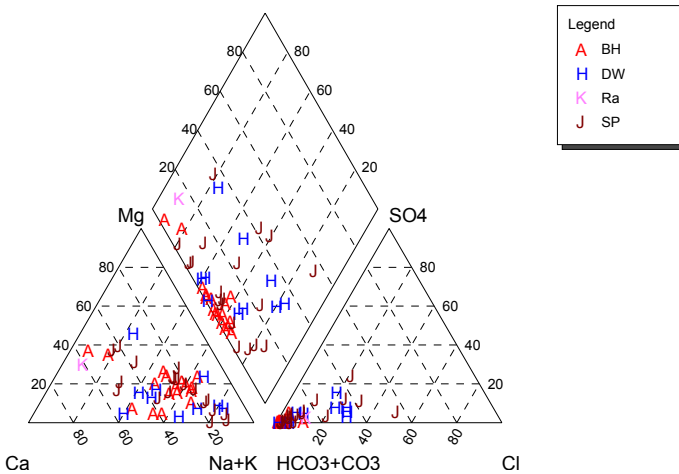


Fig 6.5 Piper plot of all sources

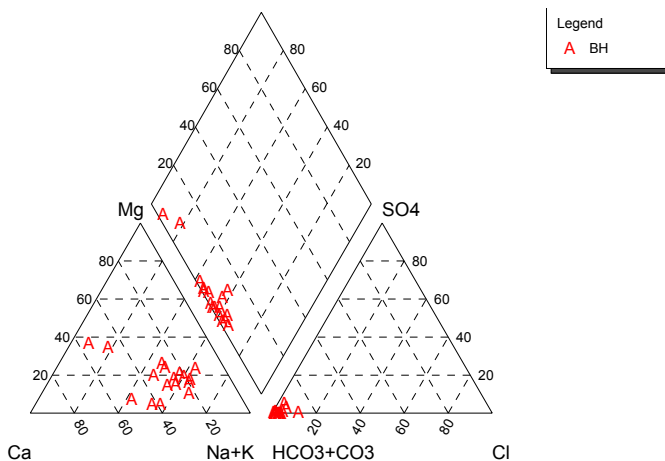
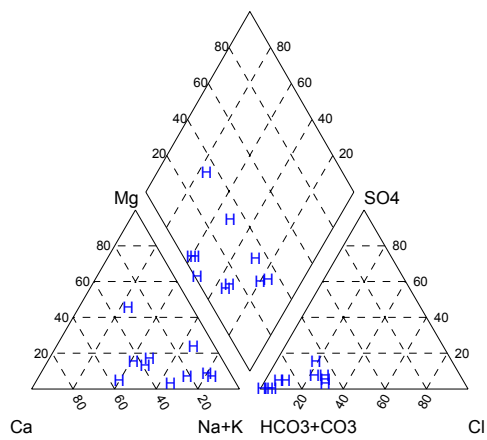
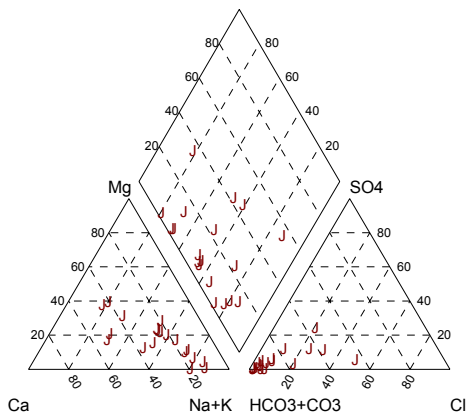


Fig 6.6 Piper plot of borehole waters



Legend
H DW

Fig 6.7 piper plot of hand dug well waters



Legend
J SP

Fig 6.8 Piper plot of spring waters

The piper plot shows that most of borehole water samples are of sodium-calcium-bicarbonate type and distinct water types are not shown on the plots that represent waters of springs and hand dug wells.

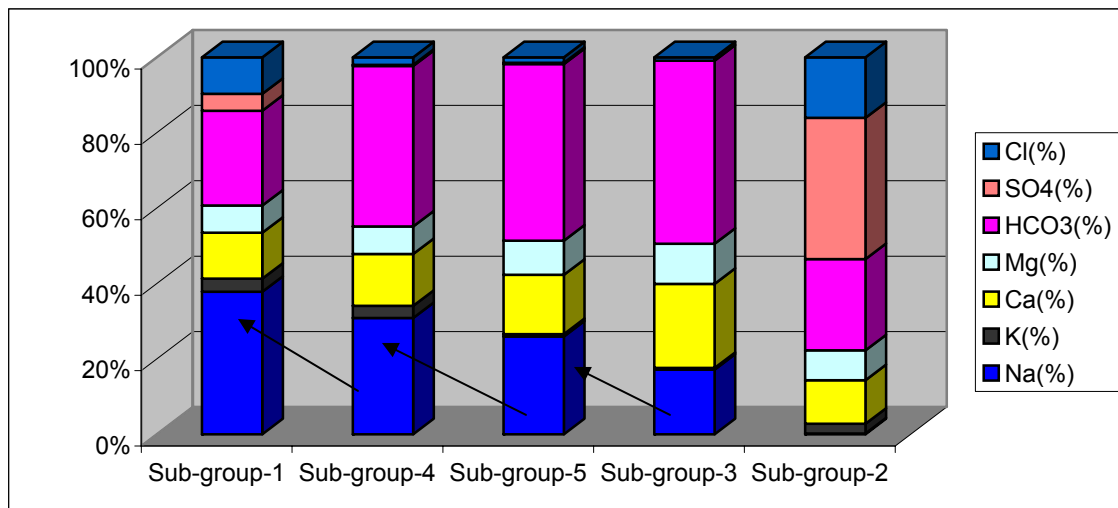


Fig. 6.9 Collins bar diagram showing increasing trends of parameters in the sub-groups

Na⁺ is almost null in sub-group-2 (water from the recharging zone) and it eventually evolves toward subgroup-3 through 1. HCO₃²⁻ concentration tends to rise in sub-groups 4,5, and 3, however, its concentration is relatively less in sub-group-1. Ca²⁺ is higher in sub-group-3 and its concentration does not show a decreasing trend in the other subgroups. K⁺ generally evolves toward subgroup-1 like Na⁺ (fig.6.9).

Schoeller semi-logarithmic diagram

The Schoeller diagram shows the total concentration of major ions in log-scale, and it allows the major ions of many samples to be represented on a single graph, in which samples with similar patterns can be easily discriminated.

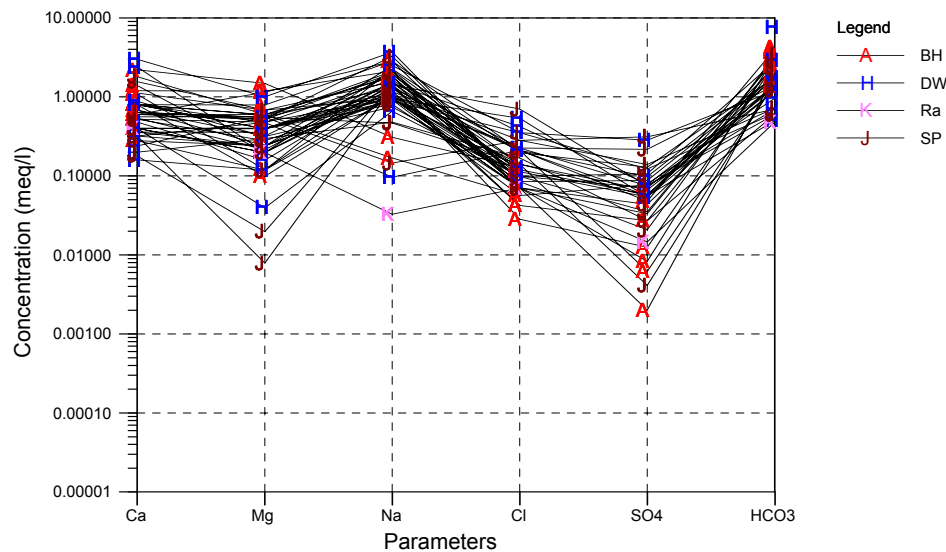


Fig 6.10 Schoeller plot of all water sources

Table 6.3 Comparison of the major anion and cation concentrations of water sources

SOURCE	Cl ⁻	Na ⁺	K ⁺	Ca ⁺⁺	Mg ⁺⁺	HCO ₃ ²⁻	NO ₃ ⁻¹	SO ₄ ⁻²	PO ₄ ⁻³	Total alkal
RAIN	0.070	0.033	0.032	0.399	0.198	0.480	0.135	0.015	0.003	24
LOW Q SP.	0.286	1.051	0.112	0.383	0.296	1.053	0.502	0.109	0.009	53
HDW	0.215	1.418	0.191	1.044	0.402	2.255	0.534	0.070	0.027	119.025
HIGH Q SP.	0.087	1.007	0.109	0.527	0.437	1.904	0.142	0.046	0.027	95.2
BH	0.092	1.426	0.093	0.896	0.513	2.623	0.085	0.009	0.040	134.92

Concentration values are given in meq/l

LOW Q SP. =low yielding springs, their yield increases immediately after the onset of rainy seasons

HIGH Q SP. = high yielding springs that show lower seasonal variability in their yield

HDW = hand dug wells

BH = bore holes

note - concentration values of each source are averaged for comparison purposes

6.5.2 Statistical presentations

The other approach to understand the chemistry of water samples is to investigate statistical relationships among their dissolved constituents and environmental parameters using multivariate statistics (Drever, 1997).

These methods have been used to determine if samples can be grouped in to distinct populations (hydrochemical groups) that may be significant in the hydrogeologic or hydrologic context.

Hierarchical cluster analysis (HCA)

The method involves the classification of samples according to their parameters and it defines groups of samples that have similar chemical and physical characteristics there by classifying the samples in to distinct hydrochemical groups based on their similarity. In other words, comparisons based on multiple parameters from different samples are made and the sample grouped according to their similarity to each other.

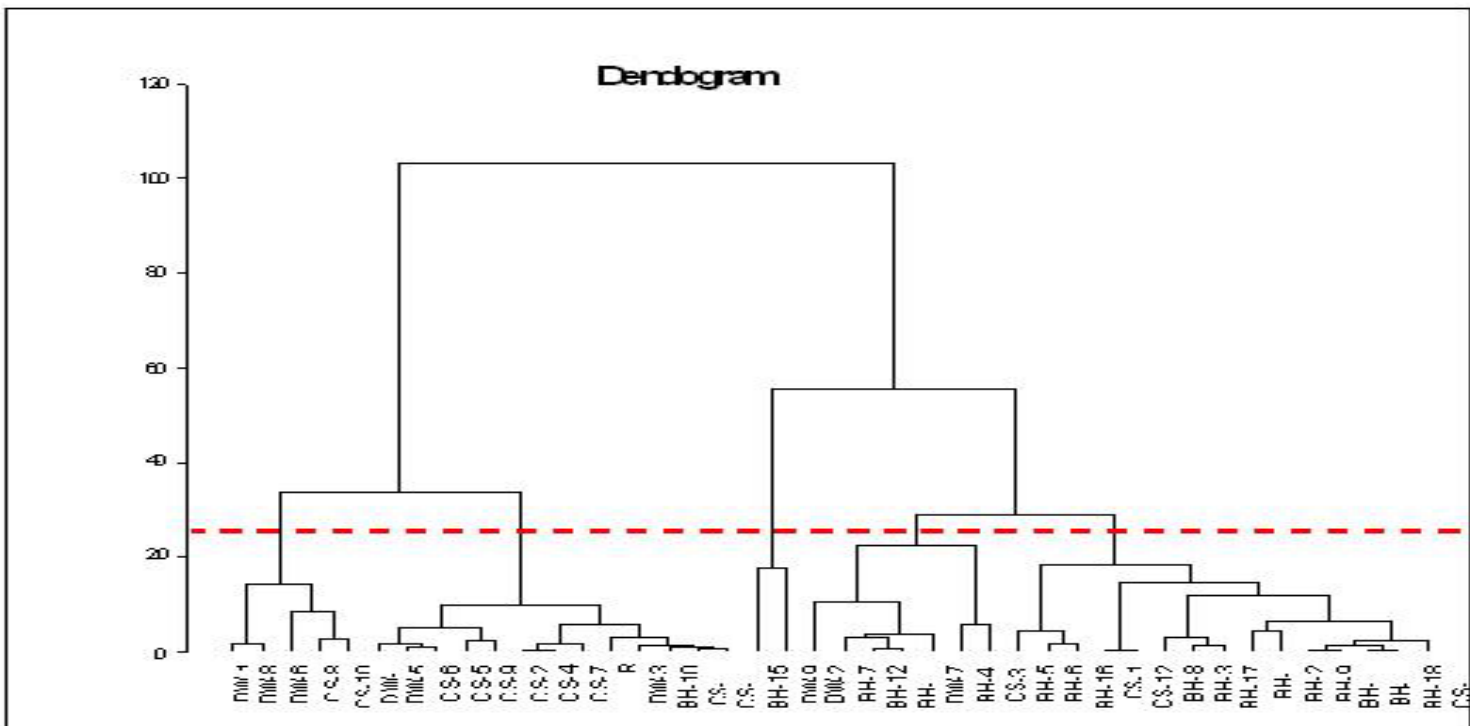


Fig. 6.11 Dendrogram from the HCA for the water samples

Table 6.4 Water chemistry of the samples subgroups determined from HCA (mean parameter values)

Sub-groups	Na	K	Ca	Mg	HCO ₃	SO ₄	Cl	TDS	Ph	EC
Sub-group-1	1.523	0.147	0.499	0.298	1.015	0.182	0.398	78.150	7.500	156.300
Sub-group-2	0.008	0.116	0.539	0.372	1.127	1.751	0.755	51.283	7.392	95.893
Sub-group-3	2.006	0.052	2.600	1.240	5.660	0.000	0.106	259.500	7.450	514.000
Sub-group-4	1.861	0.195	0.836	0.440	2.575	0.022	0.124	133.738	7.428	256.125
Sub-group-5	1.518	0.037	0.922	0.537	2.747	0.020	0.087	123.321	7.309	227.657

The relationship of the statistically defined clusters of samples to geographic location have been tested by plotting the sub-group value for each sample on the shaded relief map of the study area. Fig. 6.12 shows that there is a good correspondence between spatial locations and the statistical groups as determined by the HCA (example sub-group-5).

Aquifer interconnectivity will exist between north-east and east part of the area with its neighboring watershed, which is evidenced by same clusters of aqua-facies in the regions (clusters of sub-group-3).

Recharging waters are represented by sub-groups-2 and they are progressively evolved to Na-Ca-HCO₃-type waters (subgroups, 5,4,1). All values of the chemical parameters of each sub-group are presented in annex-6.

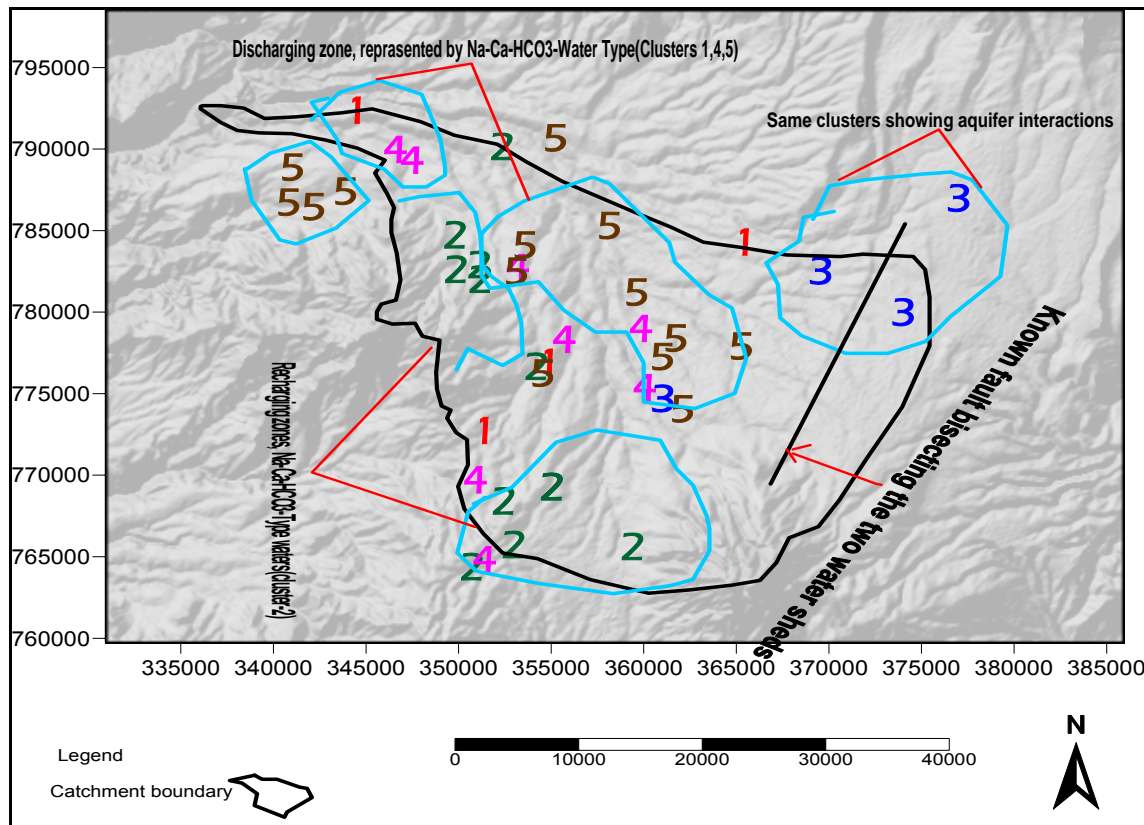


Fig. 6.12 HCA-Clusters of sub-groups showing aquifers interconnectivity, recharge and discharge zones (Sub-groups 1 – 5)

These clusters are further represented by piper diagram and analyses of evolution trends are made.

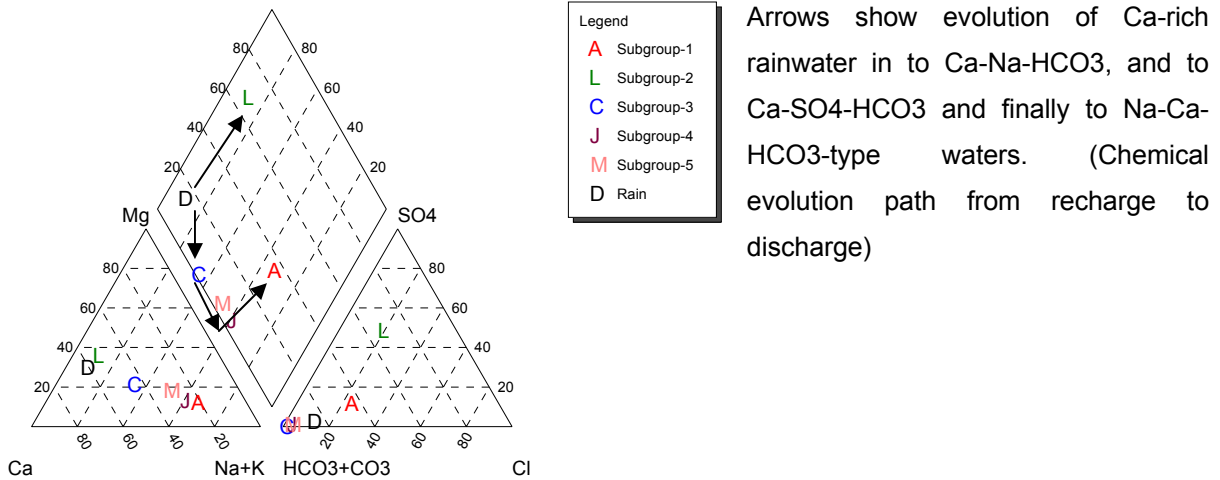


Fig. 6.13 Chemical evolution of ground water in the study area shown on a piper plot

6.6 Spatial trends of the chemical parameters of water samples in the study area and their implications to recharge-discharge zones, ground water flow directions and aquifer connectivity

Many natural factors can affect groundwater chemistry; however, the primary factors include the lithological and hydrological properties of the geologic unit, a series of chemical reactions that have dissolved material from another phase, have altered previously dissolved components, or have eliminated them from solution by precipitation or other processes, the source and chemical composition of recharge water, and the amount of time the water has remained in contact with the geologic unit (residence time) all of these factors can affect the type and quantities of dissolved constituents in groundwater.

The most abundant dissolved constituents measured are the major ions, which can be both positively charged (cations) and negatively charged (anions).

The spatial trend (evolution) of the major cations and anions for each of the sources (boreholes, springs and dug wells) are separately plotted and analyses are made on the basis of the trending direction and pattern, and on the intrinsic chemical and physical properties of the parameters.

6.6.1. Calcium, Magnesium, Sodium and Bicarbonate evolutions

Calcium ions (Ca^{2+})

The concentration of Ca^{2+} in boreholes and springs show a linear increment from south towards north-west, north and north-east, where as its concentration decreases from north-east towards south-west in hand dug wells.

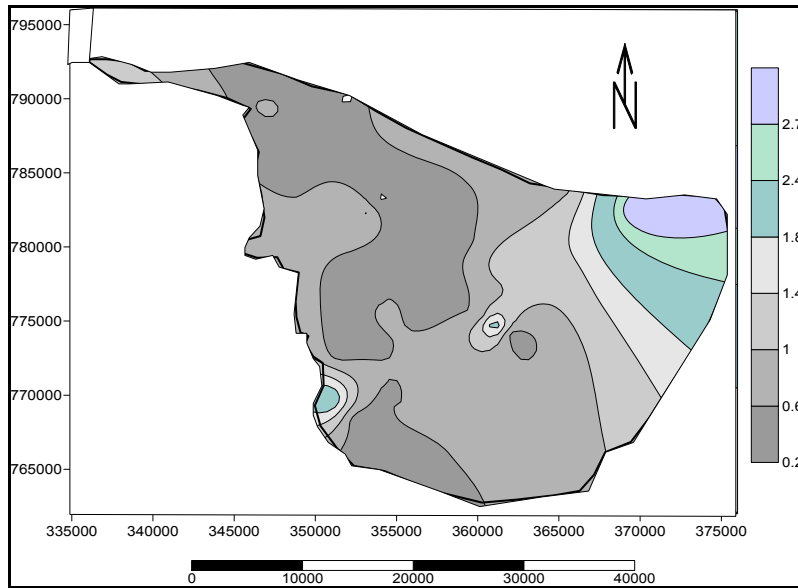


Fig. 6.14 Ca Evolution trend

Magnesium (Mg^{2+})

Magnesium evolves from south-west and south towards north-west and north-east in boreholes and hand dug wells, where as its concentration in springs is almost uniform except in the extreme north, where its concentration is locally increasing.

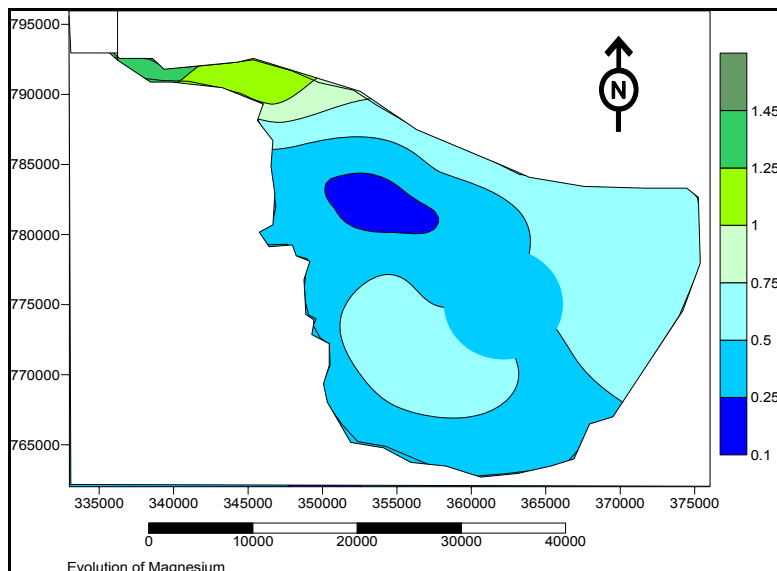


Fig. 6.15 Mg Evolution trend

Sodium (Na^{2+})

In all of the sources, Na^{2+} shows similar increasing trend from south and south-east towards north-west and north.

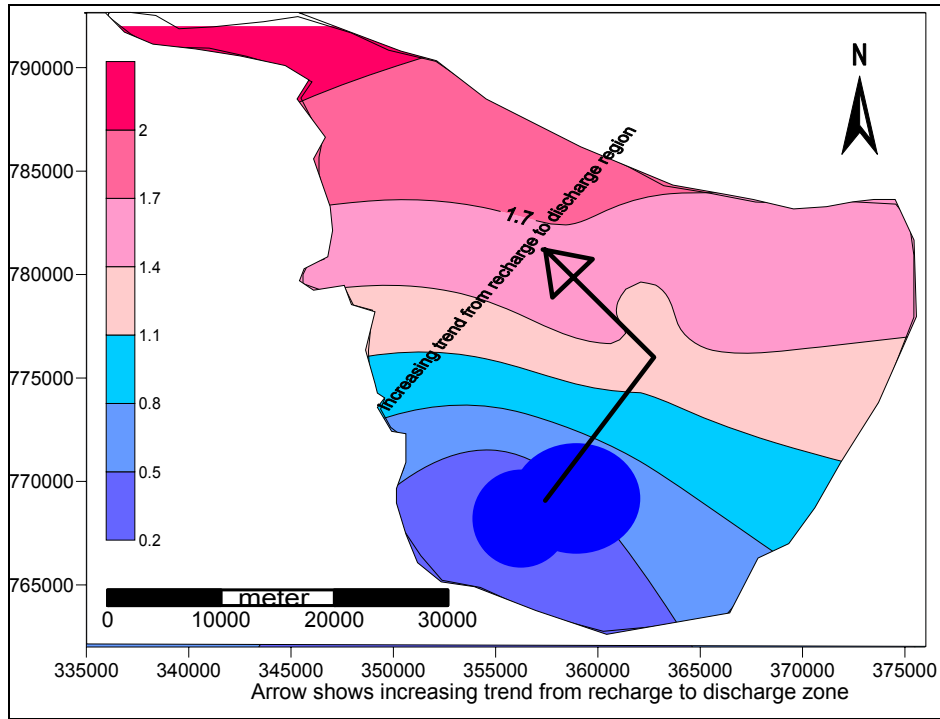


Fig. 6.16 Na^+ Evolution trend

Bicarbonate (HCO_3^{2-})

Concentration of bicarbonate in boreholes and springs show a perfect increasing trend from south and south-west toward north-west, north and north-east.

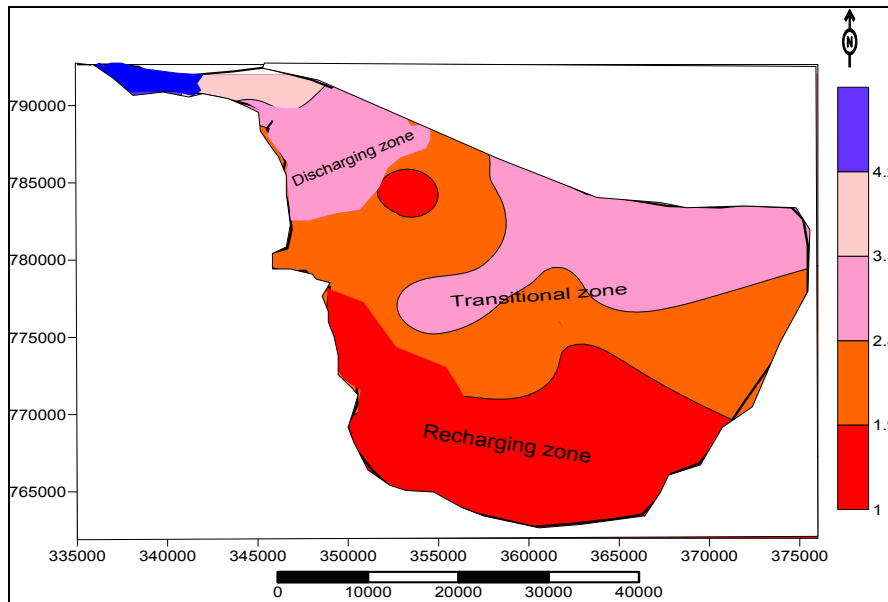
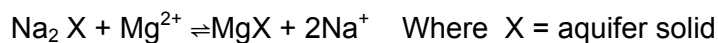
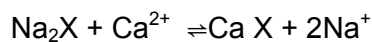


Fig. 6.17 Bicarbonate evolution (increasing) trend in the study area

The comprehensive evaluation of the chemistry of the waters in the study area reveal two distinct hydrochemical systems - a shallow and localized system generally less than 20m deep that is chemically dynamic with highly variable water chemistry (chemistry of waters of hand dug wells - look at piper plots of dug wells, fig.6.7), and a deeper, regional system greater than about 50m deep that is chemically stagnant (no significant variability of ions in boreholes) with water chemistry characterized by sodium and bicarbonate (look at piper plot of boreholes, fig.6.6).

Cation exchange is the chemical reaction frequently cited to explain the high percentage of sodium compared to calcium and magnesium in water (Lee, 1981; Woessner et.al., 1981, Wilson et.al., 1986). Cation exchange is a reaction in which the calcium and magnesium in the water are exchanged for sodium that is adsorbed to aquifer solids such as clay minerals, resulting in higher sodium concentrations (Hem, 1985).

The generalized reactions are as follow (Hem, 1985)



Ground water associated with recharge is represented by water dominant in calcium, magnesium and sulphate with lesser amounts of sodium and bicarbonate. As the groundwater flows away from the source of recharge towards north-west and north, the interaction between water and rock increases. Sodid lithologic units are encountered as the ground water moves along a flow path, and calcium and magnesium ions are exchanged for sodium ions attached to aquifer solids. Anaerobic sulphate-reducing reactions also act on the groundwater as it moves along a flow path. Therefore, both reactions result in a decrease in calcium, magnesium and sulphate and a corresponding increase in Na^+ and HCO_3^{2-} as groundwater flows away from the source of recharge and results in a water that evolves to a sodium-bicarbonate-type in the deep geochemical zone. The unexpected increasing trend in the Calcium ions concentration down the discharging zone (look at the Ca^{2+} evolution map) may be highly attributed to the effect of the geo-media in that some of the minerals forming rhyolites and trachytes (such as plagioclase feldspar and amphiboles) bear significant amount of Calcium.

The other possible justification for the typically lower concentrations in sodium, bicarbonate and calcium near recharge sources is the residence times (time in contact with aquifer materials), which is relatively short, and increases as ground water flows away from the source of recharge.

As discussed in the hydrogeology chapter potentiometric contours suggest regional groundwater flow in the study area to be north-west wards. This pattern is in a very good agreement with the apparent increase in dissolved solids concentrations toward northwest (look at EC/TDS, HCO_3^- , and Na^+ concentrations trend maps).

Recharge and discharge zones inferred from elevation contours (look at elevation contour map) are better justified by the chemical evolutions of the chemistry of the waters. At topographically high locations and from shallow hand dug wells and high land springs, water from the shallow system probably represents recharge waters and the dominant ions are magnesium, sulphate and calcium with moderate amounts of bicarbonates and low concentrations of sodium (as compared to concentrations in the discharging regions).

At topographically low locations, ground water chemistry is dominant either in sodium and bicarbonate with lower concentrations of magnesium and calcium, or is dominant in magnesium and bicarbonate with moderate concentrations of calcium and sulphate.

In general, the catchment is characterized by possessing two major recharging zones, (south-west and south-south-east), and two discharging zones (north-west and north-east), the north-west being the major discharging area, and a central transitional zone. Zonation has been made by analyzing the chemical evolutionary trends and synergizing them with hydrogeological assessments and geomorphological evaluations.

The regional ground water flow is also north-west wards with a north-east, north and north-west ward local flow patterns as inferred from the plots of the surface maps of electrical conductivity and some of the major anions and cations that help infer the flow paths of ground water.

In most cases, some of the springs and the boreholes show similar chemical composition which is remarkably deviated from the concentrations in hand dug wells, this may indicate that some of the springs are deep-sourced that cross the regional water table. This is further consolidated by the relatively similar Eh values of springs and boreholes, which are less than that of Eh values of hand, dug wells.

Connectivity of aquifers

The similarity in water type between ground water samples of adjacent catchments may suggest that there will be an interconnection between waters of both aquifers, or the waters may have

the same or similar origins or similar geochemical processes exist that control major ion chemistry in these aquifers.

Water samples in the northeast part of the study area display a more or less similar physical and chemical characteristic (Look at HCA-clusters in the shaded relief map of the study area).

Plots of the major cations and anions on a shaded relief map reveal a non-distinct boundary between the investigated catchment and its neighboring watershed to the north–east, i.e. the plot do not show higher distinction among the different parameters in that portion.

However, such a remarkable observations of non-distinct variations of parameters are almost absent in other parts of the study area. The non-distinction among the chemistry of the two aquifers in the north-east direction, is probably attributed to the connection of the aquifers and this is consolidated by:

- (i) The presence of the deep-seated normal fault (Jora-Damota) which probably acts as a bridging across the aquifers
- ii) It has been shown in the ground water budget of the study area that the sum of inflow components is greater than that of the outflows under steady state and no change in storage assumptions, the lower the outflow to some extent attributed to the sub surface flow of water along the north-east part of the area.

6.8 Chloride Mass Balance in Evaluation of Groundwater Recharge

6.8.1 Theoretical Background

The major chemical behavior of chloride ion includes: they do not significantly enter in to oxidation or reduction reactions; they form no important solute complexes with other ions unless the chloride concentration is extremely high, do not form salts of low solubility, they are not significantly adsorbed on mineral surfaces, play few vital biochemical roles, and the circulation of chloride ions in the hydrologic cycle is largely through physical processes.

Chloride ions moved with the water through most soils tested with less retardation or loss than any of the other tracers' tested-including tritium that had actually been incorporated in to the water molecules. This conservative behavior should not be expected where movement is through compact clay or shale, however (Kaufman and Orlob, 1956).

Chloride ions may be concluded characteristically to be retained in solution through most of the processes that tend to separate out other ions (Mairs, 1967).

6.8.2 Approaches and Assumptions

The method is based on the assumption of mass between the input of atmospheric chloride and the chloride flux in the sub-surface.

Ignoring the direct inputs of pollution, the fluxes for a catchment can be interpreted in terms of a mass balance equation: (Drever and Clow, 1995)

Solutes in outflow = solutes from atmosphere + solutes from weathering of minerals \pm solutes from change in biomass \pm change in exchange pool

Where, solutes in out flow = the volume and chemical composition of water leaving the catchment

Solutes from the atmosphere = the atmospheric input comes in the form of precipitation and dry deposition

Solutes from changes in the biomass = as plants grow, they extract inorganic nutrients from the soil solution and incorporate them in to plant tissue. (Plant growth may affect the budgets of most of the budget solutes; the solutes least affected are Na and Cl).

Solutes from changes in the exchange pool = exchangeable cations and anions are contained in soils that are in equilibrium with the soil solution. As the composition of the soil solution changes, ions will be exchanged between the solid phase and solution. If the soil solution composition does not change with time, adsorbed ion will not change either, and ion exchange will make no net contribution to the solute budget.

Application of the Chloride mass balance follows the following assumptions:

1. The only source of chloride in groundwater is from precipitation falling directly on the aquifer material;
2. Concentration of chloride in groundwater is by evapotranspiration with in the unsaturated zone, not from recycling, dissolution of minerals containing chloride, or inflow from adjacent aquifers;
3. Chloride is not retarded by adsorption nor accelerated by anion exclusion
4. Chloride is conservative and its mass flux has not changed over time
5. Chloride application rate is constant and known
6. There is no appreciable chloride run off or run on from the sampling sites and
7. Steady state conditions prevail.

Although the existence of these conditions may be difficult to confirm at each site, the method is applied to meet the following objectives.

1. To compare the results with the mean recharge depth obtained from other methods including water-balance, base flow recession method, and long-term mean minimum flow there by suggesting the applicability of the method
2. To test the workability of the method in such a climate and a hydrogeological environ with reference to results obtained from the conventional approaches mentioned above.
3. To forward suggestions in which application of the method is effective and improved results are achieved in the area under investigation and in others which have similar climatic and hydrogeologic characteristics.

The general equation for mean annual recharge estimation from chloride data and attributes is:

$$R = \text{PPT} * [\text{Cl}^-_p] / [\text{Cl}^-_{\text{GW}}]$$

Where R=mean ground water recharge in mm/year

PPT= mean annual precipitation depth in mm

$[\text{Cl}^-_{\text{GW}}]$ = average concentration of chloride in ground water in mg/l

$[\text{Cl}^-_p]$ =Concentration of chloride in precipitation in mg/l

6.8.3 Application and Results

The 6th assumption is thought to be violated in the specific catchment under investigation. The total amount of precipitation that carries the chloride ions is not retained with in the soil, however, part of it runs off leaving the catchment.

The mean annual runoff of the catchment, as estimated from hydrograph partitioning in to base flow and surface runoff, is about 292 mm. The mass balance method is there for adjusted to account for these violations.

The revised chloride mass balance equation can be written as:

$$R [\text{Cl}^-_{\text{GW}}] = \text{PPT} [\text{Cl}^-_p] - \text{RO} [\text{Cl}^-_{\text{RO}}]$$

Where RO = mean annual runoff in mm and

$[\text{Cl}^-_{\text{RO}}]$ =concentration of chloride in water that runs off after Precipitation

The concentration of chloride in the run off is thought to be the sum of the concentration of Cl⁻ in precipitation and chloride concentration in the unsaturated zone - because, during runoff, some amount of concentrated chloride that is contained with in the top layer of the soil pores are removed by the running water. This amount is accounted in the total concentration of chloride in runoff. A bold assumption is made by the author of this research project that approximately 30%

of the total concentration of chloride in the ground water will be removed from the unsaturated zone by the runoff.

Recharge from precipitation calculated by using the above equation yields:

$$R = \frac{\text{PPT} * [\text{Cl}^-]_p - \text{RO} [\text{Cl}^-]_{\text{RO}}}{[\text{Cl}^-]_{\text{GW}}}$$

PPT = 1341 mm/annum

RO = 292 mm/annum

$[\text{Cl}^-]_{\text{GW}} = 12.4 \text{ mg/l}$

$[\text{Cl}^-]_p = 2.5 \text{ mg/l}$

$[\text{Cl}^-]_{\text{RO}} = (2.5 + 30\% * 12.4) = 6.22 \text{ mg/l}$

R = 123.89mm/annum

The recharge value obtained by using this method is substantially higher when compared to the values obtained from the other methods. This elevated value will be mainly attributed to:

- i) The monthly distribution of precipitation i.e. precipitation is continued with a short break from March to September with a variable depth (look at graph showing the monthly precipitation trend in the area). The chloride that is concentrated by the evapotranspiration with in the short break (gap) will be removed prior to percolation.
- ii) The depth of surface run off shows an increasing trend (as described in the hydrology chapter). This may also have a significant effect on the concentration of Cl^- with the soil water.
- iii) Measurements of Cl^- in the laboratory is carried out by titration method. This method is in most cases associated with subjective determination while observing colour changes. The recharge rate determined by using the above equation is very sensitive to the average chloride concentrations. For instance a 0.5mg/l change in Cl^- concentration in precipitation changes the recharge by over 38 mm and a 1mg change in Cl^- concentration in groundwater changes the recharge by about 15 mm.
- iv) More data on Cl^- contraction, especially in precipitation has not been collected
- v) Estimation of either surface run off or precipitation may lack perfection. The uncertainty out weights on the estimation (computation) of run off.

In conclusion, this approach is fairly working in areas where the precipitation do not have a bimodal trend and non-continuous; surface run off is absent or very minimum, chloride is concentrated by evapotranspiration and there are no other chloride sources. In the case of the area under investigation, to improve the workability of the chloride mass balance approach in evaluating ground water recharge.

- i) Measurements of concentrations of Cl^- in precipitation in a multi-year series at different seasons should be made
- ii) The laboratory measurements should take precision and accuracy in to account and repeated measurements of same sample is highly recommended
- iii) The chloride concentration in the unsaturated soil-zone should be precisely measured at different seasons
- iv) The amount of chloride that will be removed by run off from the unsaturated soil horizon should be reasonably estimated
- v) All the inputs that make up the balance such as mean annual depth of precipitation, and runoff, should be carefully estimated, computed or measured, which, in fact, is quite crucial for the rest of evaluation and assessment techniques of the resource.

7. Hydro geophysics

7.1 Theoretical Background

Geophysical exploration methods are among the primary tools for the investigation of ground water resources and are applicable to a wide range of problems. Among the various techniques of geophysical prospecting, the electrical methods have branched out from a broader and more basic discipline geoelectricity, which utilizes the electrical properties of rocks and soils. Among the highly diversified techniques, electrical resistivity is the one most extensively used in prospecting for groundwater resources. In this method a direct current or a low frequency alternating current is introduced into the ground using a pair of electrodes and the resulting distribution of the potential in the ground is measured by using another pair of electrodes connected to a sensitive voltmeter.

The variation of resistivity with depth is studied by a progressive increase of current electrode separation so that the effects of rocks at depth will be more significant. This method is known as vertical electrical sounding (VES).

Resistivity value is determined from the relation developed using potential drop, measured current and the geometrical configuration of the electrodes. If the ground is homogeneous the resistivity calculated would be independent of electrode spacing and location. But in reality, since the real ground is locally heterogeneous both laterally and at depth the resistivity varies with the relative position of electrodes.

The sub-surface material resistivity variation affects the electrical current flow lines and these in turn affect the distribution of surface electrical potential lines, compared to their pattern over a homogeneous medium. The apparent resistivity (ρ_a) is then computed.

The usefulness of the resistivity method in solving geological and hydrological problems depends to a considerable extent on the sub-surface resistivity contrast. In considering the resistivities of various geologic units it is found that the overall resistivity is very sensitive to variation in porosity, water content, and water quality (ionic concentration) and can be considerably lower than the resistivity of the rock matrix (Kearey, et al., 1984).

7.2 Objectives of the survey

The major objectives of carrying out VES surveys in the study area lies mainly on estimating depth to the deepest aquifer formation for there are no bore holes with a depth greater than 180m. The other major objective of the survey was to fill data gaps while interpreting the hydrostratigraphy of the study area where there are no boreholes and borehole logs.

The survey is also aimed at characterizing the different geo-electrical layers in terms of their hydrologic and hydrogeologic significance.

- Estimating depth to shallow and deep aquifers
- Map sub-surface stratigraphy of areas that are devoid of borehole logs
- Assess the presence or absence of contrasting layers with clear and contrasting values of apparent resistivity there by testing the extent of applicability of the method in such hydrogeological terrain
- Characterization of the sub-surface geo-electric layers in terms of their hydrogeologic and hydrologic significance.

7.3 Methods and Materials

Prior to conducting the VES's in the area, preparations of base map that reveal two features have been made.

i) Plotting all the available boreholes (which have lithological logs) on the base map and delineating those areas which lack litho-log information.

ii) Plotting the direction (orientation of survey line) where greatest contrasts are thought to be obtained

iii) Conducting VES on already drilled borehole that has a well mapped and described lithological log in a view to have an overview on the apparent resistivity values.

All sounding data measurements were made using ABEM TERAMETER – 4000 which is powered by car battery, copper and stainless steel electrodes for transmitting current in to the ground and for the measurements of potential difference and four wheels with a cable length of 750 for current and 90m for potential spreads.

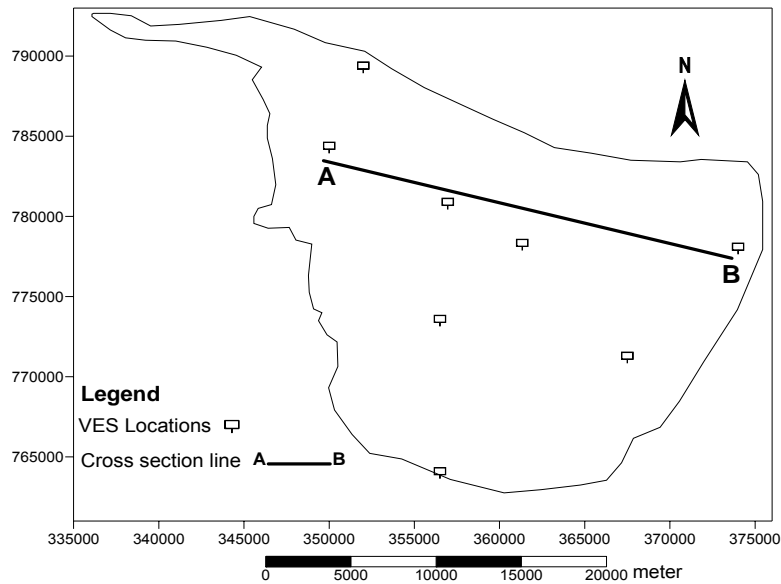


Fig. 7.1 VES sites location and line of cross section

7.4 Interpretation and analyses of VES data

Interpretation of raw data has been carried out both manually and using a computer code known as RESIST that iterates for a number of times the raw data input and the manually interpreted results.

The field curves that are a plot of the observed or measured apparent resistivity, ρ_a , over a wide range of electrode spacing $AB/2$, are interpreted with the help of standard (master) curves. This has been done by drawing the field curves on a transparent paper with the same modulus as that of the standard curves. The number of inflections in the field curve indicates the number of layers explored by the resistivity method. The interpretation consists of matching the field curves with one of the master curves. Matching is done by moving the field curves over the master curves keeping the coordinate axes parallel; and the match gives the model of the earth under investigation.

The computer code, Resist, for the iterative interpretation methods handles horizontally layered earth situations. The input to the program consists of the resistivities and thicknesses of the layers and the output consists of a series of plotted points, which then joined up to form the apparent resistivity versus electrode separation.

7.4.1 General overview of VES results, presentations, analyses and discussions on specific and representative VES results

General over view of VES results

- A thin layer of highly resistive top soil with an average soil thickness of 1.3m in all of the areas (VES sites) with an apparent resistivity values ranging from 200-670 Ω -m, is observed.
- Interpreted number of earth layers range from 5 to 7, in most cases 6, in both iterated and manually interpreted results.
- The least resistive layers (with an apparent resistivity values of 1 - 4 Ω -m) are explored at a depth range of 20-30m in most of the surveyed areas. Still very low resistivity values are obtained below 140m at the central part of the study area that gives a value of 1 Ω -m (VES location 356958 mE, 780800 mN, 1747m.a.s.l).
- Even if the current electrode separations are extended up to 1500m (750m each side), the interpreted results show a maximum depth penetration of \approx 190m and a minimum of \approx 90m.
- The deepest penetration of current is attained at a VES location of 375143 mE, 787145mN, 1737m around a locality known by the name Gidohomba, this area is the discharging zone; and the shallowest penetrations obtained at Sorfella plain (the southern boundary of the study area and is the recharging zone) at a VES center of 357974mE, 760800mN, 1925m.a.s.l.
- The maximum apparent resistivity value that is attained at the most bottom layer is \approx 200 Ω -m (VES-location: 354802mE, 778490mN, 1833m) at the South-Western part which is a partially recharging zone; and the maximum values in the rest of the surveyed areas ranges from 40-100 Ω -m.
- Thicknesses of anomalously low resistive layers range between 15-20m in all of the surveyed areas, which is in a very good agreement with the thicknesses obtained from borehole logs and cuttings of hand dug wells.
- As inferred from the VES result that is carried out at a location where there is a borehole with proper well completion data, the low resistivity values are correlated to a deeply weathered, saturated trachyte. However, this formation, even if it possesses low

resistivity, does not yield high amount of water. The estimated discharge of the borehole is 0.5l/se.

- In most of the VES sites, the presence of hand dug wells that have a depth of 14-28m, help infer the depth of shallow aquifers which is in a good agreement with the resistivity values of the shallow layers. These layers have an apparent resistivity values that range from 1-10 Ω -m, and crop out at a depth of 10-30m
- In general, it could be said that the apparent resistivity values of the middle layers do not show a high contrast among values i.e. they do not show noticeable differences that could actually exist and observed from hand dug and borehole logs.

7.4.2 Presentation of Results

The results of VES's are presented in such a way that correlation between different VES points is easily made. To make this possible, the most representative VES results and their respective locations are presented in cross section that display depth versus apparent resistivity values. Figure below show the apparent resistivity variations with respect to depth of some representative VES results.

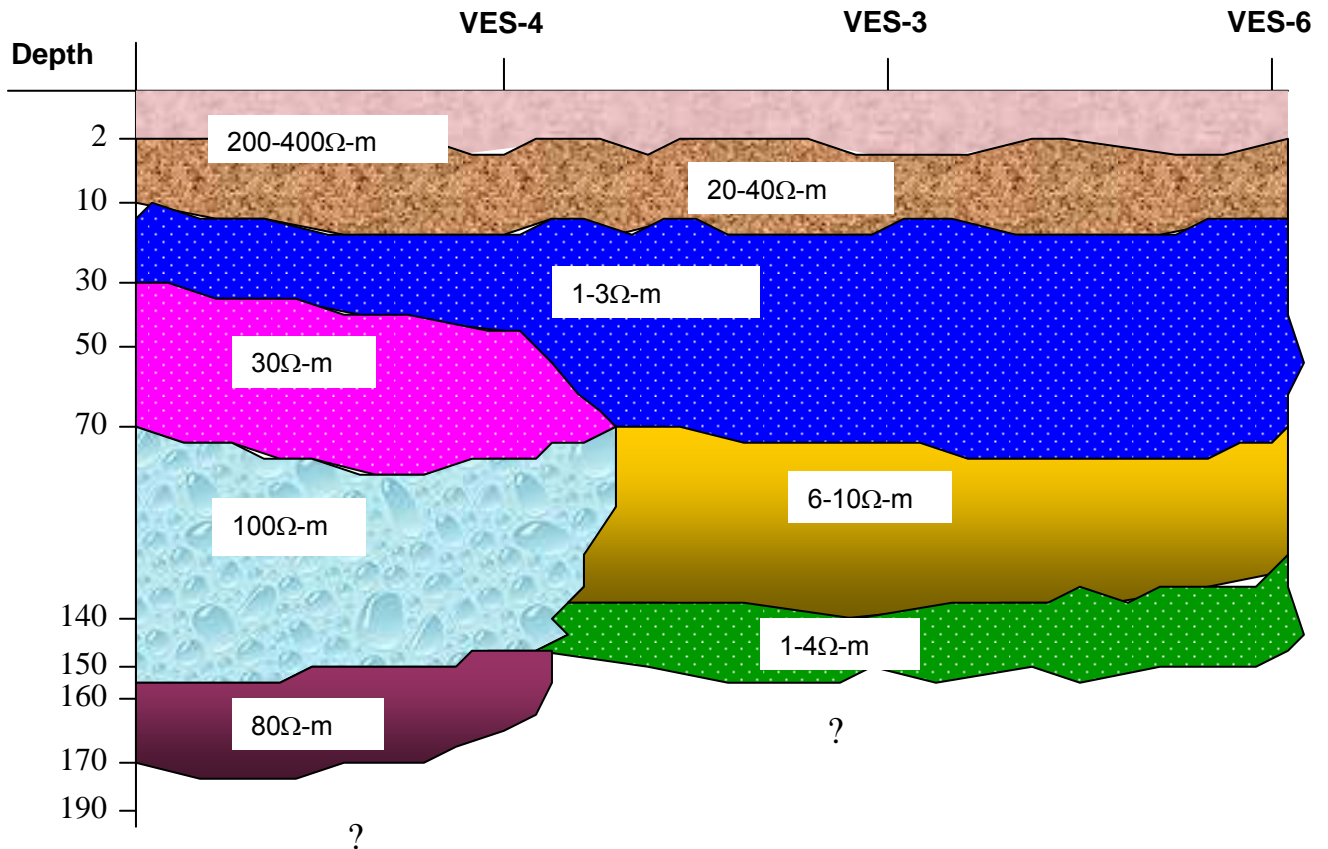


Fig. 7.2 VES-Cross section along A-B
89

7.4.3 Interpretations and discussions on specific and representative VES results

Interpretations of the variations of apparent resistivities both laterally and at depth, in the study area reveal three important conditions. The facts are consolidated by the hydrological and hydrogeological findings that are discussed in the previous chapters.

i) VES results that are obtained from the central part of the catchment reveal a thick weathered column that has an estimated thickness of 40m to 60m (ρ_a ranges from 1-6 Ω -m) which is in a very good agreement with results of hydrogeological assessments. This thick and deeply weathered unit overlies a moderately weathered unit of probably the same formation that possesses a measured apparent resistivity value of $\geq 10\Omega$ -m having a thickness of 50-70m. All these formations overlie a hydrogeologic unit that has an apparent resistivity of 1 Ω -m and crop out at a depth of below 140m. The thickness of this formation is not known due to the limited penetration depth of electrical currents at this VES location.

The hydraulic conductivity values of these areas are relatively lower than the values obtained at the north-eastern parts of the study area, however the electrical resistivity values are almost comparable with the north-eastern portion of the area. This opposite concepts could possibly be justified in two ways:

The first and the strong reasoning lies in the hydrogeological properties of the rocks that form the study area. These rocks (the pyroclastic flows and falls, in general) have low or no primary porosity (in most cases) and the aquifers of these rocks are mainly controlled by secondary processes especially by weathering and fracturing. As it is explained in the hydrogeology and local geology sections of this research project, the north-eastern part of the area is faulted and the faulting controls the hydrogeologic properties of the rocks in producing higher hydraulic conductivity and there fore lower electrical resistivity. The central part of the study area (that displays a comparable electrical resistivity but lower hydraulic conductivity than the north-eastern part) is dominantly covered by moderately to deeply weathered pyroclastic flows and falls (especially welded tuff and rhyo-ignimbrites) of thickness ranging from 40-100m and $\rho_a \approx 1$ -10 Ω -m, this shows that in such a hydrogeologic environ, weathering plays relatively less important role than fracturing.

ii) VES results obtained from Sorfella plain, a plain situated in the southern divide of the study area, are partially expected and partially unexpected. The plain divides the study area from the southern and south-western neighboring water- shed. No fresh lithologic units are outcropped in

the plain except slightly weathered pumaceous deposits that are exposed along road cuts. The streams in the plain are not well developed and all are seasonal. The delineation of the boundary in the southern divide is made on the basis of the drainage patterns developed on the plain. It had been thought that the plain is formed from massive and relatively fresh volcanic flows that are overlain by relatively thick alluvial deposits transported from the eastern, Damota, and western Afama, highlands. However, these thoughts are changed after the VES results that show an appreciable thickness of moderately to deeply weathered pyroclastic units that possess an apparent resistivity in the order of 4-16 Ω -m and a thickness of 50 to 90m. On the other hand the results are thought to indicate that the southern divide has no geomorphic nature, rather the divide is formed by an east-west running deep seated fault which is bounded from west by Afama ridge and east by Gurumo Koisha (Damota) ridge.

It is highly recommended that lateral inhomogeneity hunting to be carried out around this area that has a surveying line orientation of north-south.

iii) VES results obtained from Legama (VES location: 361333 mE, 0778241mN 1820m) are highly correlated to the borehole log thicknesses and depth, moreover yield of the wells and the measured apparent resistivity values give a good reasoning to the poor yield of the wells that are drilled around this locality. Two of the wells are drilled to a depth of 75 and 55m at two opposite ends of the locality; borehole logs show that in both of the wells weathered welded tuff is the main aquifer formation that crop out at a depth range of 25 to 40m and possess a thickness of 10 to 15m. The apparent resistivity values at these depth ranges show relatively higher values when compared to the resistivity values at the central and discharging zones of the study area.

In conclusion, it could be possible to say that anomalously lower apparent resistivity values in such a hydrogeologic terrain, does not mean that the formation is saturated and a good water bearing. However, interpreting these values in conjunction with the hydrologic and hydrogeologic behaviors of the litho-units and with geological phenomena, are quite crucial.

Moreover the higher contrast among apparent resistivity values of successive layers should be obtained to classify layers on the basis of the magnitude of resistivity so that over interpretations are avoided. Over interpretation of apparent resistivity values in such a geologic set-up may lead to an over estimated number of layers, which in turn misleads the exploration and exploitation activities of the resource.

8. Discussions and conclusions

Assessment of the surface and sub-surface water resources majorly targets on the description and mapping of the lithological units, local and regional geological structures, quantification and qualitative descriptions of the hydrologic parameters including precipitation, surface runoff, groundwater run off, actual and potential evapotranspiration, and groundwater recharge.

In addition, characterizations of the hydrogeologic elements that have a paramount significance in controlling the potential of the ground water resources, mainly the hydraulic conductivity/permeability, ground water flow systems and modes of interactions with other systems, and the chemical and physical parameters, both field and lab-measured are among the tools that greatly facilitate evaluation of the resource.

Lithological units and geological structures

The ground water potential of the study area is majorly under the control of the hydrogeologic properties of the litho-units and associated structures. Four different lithological units outcrop in the study area. Ignimbrites (welded tuff) cover a wider portion, trachytes, rhyolites and minor flood basalts, all tertiary, Miocene to Pliocene age. Recent alluvial deposits in the central, north-west and south (Sorfella plain) overlie the tertiary volcanics.

A known normal fault that runs from N-E to S-W in the eastern part of the catchment; and inferred faults that run from NW to SE, dividing the Weybo and Sokie catchments, and a buried inferred fault in the extreme south of the catchment that crosses the Sorfella plain in E-W direction are among the structures in the area. The spatial arrangements of these geological elements have seen to control the potential of the groundwater system that is interpreted in terms of the hydraulic permeability of the units and the relation of permeability with the structures.

Weathering of the litho-units is the major process that produces secondary porosities.

One known and two inferred fault systems are identified. The known normal fault has seen to play a role in controlling the hydraulic conductivity of the rock units in the east and north-east parts of the catchment. The two inferred faults are thought to be surface water divides and their role in controlling the permeability is not well understood. It could be said that these two inferred faults are either acting as a barrier or they do not significantly affect (disturb) the rock masses or

they are very deep seated where there effects might be encountered at depth or they may be in existent.

The secondary porosities produced only by weathering of the units do not yield a good permeability aquifer; where as significant variations are seen in hydraulic conductivities of the units that are affected by the north-east – south-west running fault.

Hydrologic parameters

Effective aerial depth of precipitation obtained from the three different methods show low variations. This low variation among the results is mainly due to two factors: **(i)** nearness of the meteorological stations to each other and low topographic differences, and **(ii)** stations are distributed in zones of low to medium climatic variations. The median of the three results has been taken in order to incorporate the effects of each method. The area receives an annual mean precipitation of 1341 mm.

The actual evapotranspiration is quantified by applying both empirical formulae and the soil-water balance approach developed by Thornthwaite and Mather 1957. Turc, Thornthwaite and Crowe-Thornthwaite methods yield 884.96, 153.88 and 859.6mm respectively. The results obtained from these methods underestimates the actual values. The reasons for the underestimated values might be seen in two ways:

- i)** Three of the empirical formulae use only temperature and precipitation, which do not account for the effects of the rest hydro-meteorological, pedological and botanical (land-use-land-cover) effects on the rate of the actual evapotranspiration.
- ii)** These empirical formulae are developed for specific climatic regions, which may not work for a different one.

Results obtained from the soil-water balance (=960.3mm/annum) thought to represent the actual evapotranspiration of the study area for three reasons:

- i)** It is computed on the basis of the measured mean precipitation of the area and the potential evapotranspiration, which is computed by the penman approach. The potential evapotranspiration obtained from penman incorporates a number of hydrometeorological parameters that have a direct effect on the rate of potential evapotranspiration.

ii) The available soil moisture, field capacity of the soils and root depths of the vegetal cover controls the rate of the actual evapotranspiration from an area, however, these controls are not incorporated in any of the empirical formulae.

iii) The higher actual evapotranspiration obtained from the soil-water balance method signifies a lower moisture deficit, i.e. the evapotranspiration is taking place in its potential rate which is true for the fact that the mean precipitation in most of the months exceeds the potential evapotranspiration rate.

The surface water and groundwater runoff computed from partitioning the stream hydrograph of Weybo River. The total runoff of the catchment is extrapolated from flow values measured at a gauging site located in one of the sub-catchments of the Weybo river catchment. The extrapolation involves scaling up of flows of the sub-catchment on the basis of area-ratios and simulation of the flow in the catchment with the analogue sub-catchment on the basis of depth of precipitation and aerial extent. In both cases similarity in surface phenomena that control/govern the flow rate and volume are taken in to consideration.

Partitioning the surface and ground water runoff has been made both manually and with the aid of computer software that takes an attenuation coefficient (which is a factor of surface slope and land cover and land-use) in to account. There are moderate variations in the results obtained by the two methods. However, both of the methods show some degree of subjectivity, (while partitioning), the effects of the two methods are incorporated by simply averaging the resultant values.

The surface runoff in the catchment shows an increasing trend where as the groundwater runoff is decreasing in an appreciable rate. The decrease in annual precipitation of the catchment, however, is not comparable to the significant decrease in the rate of baseflow.

Groundwater recharge is computed using different methods. Five different methods, that include the base flow recession method (Meyboom, 1961, Fetter, 1994), the mean minimum stream flow (Fetter, 1994, Meyboom, 1961) the conventional water balance (Shaw et.al., 1988) the soil-water balance (Thornthwaite and Mather, 1957) and the chloride mass balance (Eriksson and Khuanakasem, 1969, Plummer, 1980, Murphy and Ginn 1996) have been applied and five different recharge values are obtained. Selection of reasonable values of recharge is made on the basis of the annual ground water balance under a steady state and no storage change

conditions. Accordingly, averaging the recharge values obtained from the conventional water balance and the base flow recession methods show a fair balance with the ground water budget.

The very important observation to be discussed in connection with the temporal variability of ground water recharge is its noticeable declination for the last 15 years. The decreasing trend has been evaluated in lights of the major hydrometeorologic parameters including the trends of mean annual depth of precipitation for the last 18 years, trends of surface run off for the last 15 years, trends of temperature, wind speed and potential evapotranspiration in the area.

The temporal changes in amounts of precipitation is not highly correlated to the significantly changing trends of groundwater recharge, i.e. even if precipitation is declining, the rate of declination could not able to bring a significant declination of recharge (like the existing situation). The surface run off shows an increasing trend, temperature and wind speed are also increasing, the potential evapotranspiration is slightly increasing. All these changes of parameters are greatly associated with the changes of the environment. These significant changes will bring measurable changes in ground water storage after 30 years period. Moreover, it is possible to project these effects on to the entire Omo-Gibe basin since the investigated area is part of the basin.

The overall assessment of the hydrology of the catchment shows a positive balance, and a very small amount of water is being consumed, however, it has got to be known that, even though there exists a positive balance among the hydrologic components, the ground water recharge condition is affected and will be severely affected if environmental conditions are changing at the existing rate.

Hydrogeologic controls

The ultimate goal of characterizing the major hydrogeologic controls (that are intrinsic to the lithology and associated structures) is in order to effectively characterize the hydraulic permeability (conductivity) of the system.

Three different aquifer formations are outcropped in the study area. Fractured and weathered ignimbrite (welded tuff), weathered and fractured trachytes and rhyolites, and alluvium. Thicker aquifer formations are mapped in the central and north-west zones of the study area. This thick formation is due to in-situ weathering of the parent rock unit and deposition of sediments.

Hydraulic conductivity ranges obtained from pumping test analyses of boreholes that are drilled along fault lines and in the weathered portions show observable variations. Generally the hydraulic conductivity of the boreholes that pump water from weathered aquifer formation (weathered ignimbrite, rhyolite and trachytes) ranges from 0.1-0.5 m/day, where as those that are drilled in fractured and weathered formations of the same rock mass possess a hydraulic conductivity values greater than 0.5m/day.

It has also been observed that the intensity of weathering has an effect on the permeability of the aquifer systems in that deeply weathered acid pyroclastics which crop out in the central (and extended to some parts in the north-west) possess still a lower hydraulic conductivity (K in the order of 0.1-0.3m/day) and moderately weathered rocks that crop out in the southwest, south-east, south, partially central and partially north-west portions of the study area possess a relatively higher hydraulic conductivity that reaches up to 0.5m/day. In general it could be said that the variation in the permeability of the aquifer units in the study area is controlled by secondary processes mainly weathering and fracturing.

The regional flow direction of the groundwater system is generally north-west wards, and local flow systems are observed in the recharging and central zones from a plot of the hydraulic heads of the available groundwater sources in the area. From the same plot the groundwater divides from west and east have been shown following the directions of the flow vectors. The surface water divides coincide almost in a perfect manner at these two locations. Lack of hydraulic head data in the northern and southern parts of the neighboring watersheds limit to conclude that the ground water divide is perfectly symmetric to the surface water divide.

The ground water budget in annual basis shows inequality between the inflow and outflow components. The inflow component (i.e. the mean annual ground water recharge) exceeds the outflow by an amount of $\approx 3\text{mm/year}$. One of the justifications for the un-balanced situation might be the non-symmetry of the surface and ground water divides. The ground water may flow to adjacent catchments where the groundwater divide is beyond the surface water divide; or there may exist an under flow either at the stream flow gauging site or somewhere in the line of the streambed. The other probable reasoning will lie on the precession and accuracy in determining the groundwater run off (base flow). Out of these reasoning, two of them may give sound for the inequality. The first one is the subjective nature of the base flow separation, the subjectivity of the technique may contribute to the under estimation of the out flow values. The other one is migration of groundwater through the inferred groundwater out flow zones following

the structural conduits. This is further evidenced by the similarity of the waters in the east and north-east part of the catchment and its neighbouring catchment.

Existence of the interaction of the surface water and ground water systems is evidence by physical characteristics that rely on the head differences between the hydraulic heads of the ground water system and the elevation of the streambeds. A plot of contours of the hydraulic heads and the stream networks reveal that most reaches of the stream gain water from the groundwater system and those that are at the lowest reaches (and partially at central zones) lose water to the sub-surface system.

Hydrochemical controls

Measurements of the major cations and anions, and the in-situ field parameters have been used in a view to show:

- i) Recharge/discharge zones, regional/local/intermediate flow systems through mapping the increasing/decreasing trends (evolutions) and associating the trends with the intrinsic chemical and physical properties of each parameter
- ii) Aquifer interconnectivity and source/origin by clustering (grouping) water types (aqua-types)
- iii) Applicability of the chloride mass balance to evaluate the groundwater recharge

Mapping concentration trends of HCO_3^- , Na^+ , Ca^{2+} , Mg^{2+} , Eh, EC, and pH in a 2-dimensional scatter plot show a very good correlation of the parameters. Four of the maps clearly mark the recharge, discharge and transitional zones and the EC contours show the regional and local flow systems that are in a good agreement with the results obtained from hydrogeological assessments.

However, Ca^{++} tends to show an increasing trend toward the discharging zone. The enrichment in Ca^{++} might be justified in such a way that the minerals that bear calcium in the area (such as plagioclase feldspars that are major components of felsic pyroclastic rocks) may be incorporated to the water system during weathering.

Both statistical and graphical presentations are used in order to facilitate the interpretation and analyses of the chemical data. Most of the water types collected from boreholes are Na-Ca- HCO_3 , whereas most springs and dug wells do not show a distinct water type.

The groundwater recharge estimated from measurements of chloride in rain water and ground water yields an over estimated result when compared to the results obtained from seasonal base

flow recession, conventional water balance approaches and the mean minimum stream flow method. Five probable, one of which is deterministic, justifications have been forwarded for the higher result.

T

Apparent resistivity values

A broad distinction has been made between the weathered and saturated column and the fresh/slightly-weathered column of layers. However detailed classification of layers on the basis of their apparent resistivity was not effective for the layers bounded between the top unsaturated dry soil column and the very bottom fresh/slightly weathered column (if that part is encountered). This is because in most sites where the survey is conducted, these medium layers do not show contrasting values. It is, then, possible to say that water resources potential investigation applying geophysical techniques like vertical electrical sounding, in such geologic medium have got to be supported by hydrogeological assessments. The lower contrast in resistivities of the different medium layers may result in failures in interpreting the aquifer layers.

The apparent resistivity values show two important situations in this hydrogeologic terrain:

i) They do not show appreciable correlation with the hydraulic conductivity values. This phenomenon is seen in the central and north-eastern parts of the study area. In both locations the apparent resistivity values are more or less similar and generally low; where as the hydraulic conductivity values are significantly differ to each other in that they are appreciably higher in the north-eastern part where it is transacted by a known normal fault structure.

The apparent resistivity contrasts in both media (i.e. the central and north-west weathered zone, and the north-east fractured zone) do not give sound differences as it is seen in the hydraulic conductivity changes. It might be inferred that ground water localization is greatly effected by fracturing of these acid volcanics than by weathering of these rock bodies provided that the faults/fractures do not act as a barrier for the movement of water in the sub-surface.

ii) Spatial changes in apparent resistivity both thickness and depth wise have closely related to the characteristics of the three hydrogeologic zones. It has been observed that the lower electrical resistivity values in the recharging zones are encountered at depth and they generally possess smaller thickness; where as these lower values are encountered at relatively shallower depths and possess thicker columns in the transitional and discharging zones. This could imply

that identification of hydrogeological zones could be inferred from results of vertical electrical soundings, and the results should have to be consolidated by hydrogeological investigations.

In conclusion, synergizing all the adopted techniques have seen to facilitate the assessment of the resource and help in obtaining reliable estimates of the major controlling parameters of the surface and the sub-surface systems, there by enhancing our degree of certainty on the resultant outputs.

Recommendations

Recommendations are set based on the findings and observations that strictly focus on the following two points:

- i) Measures to safeguard the sustainability and enhance the productivity of the resource of the investigated area in particular and the basin that contains it in general
 - ii) Solutions to enhance the degree of certainty of measurable or computable parameters that control the potentialities of the resource
- The ground water recharge has kept and will keep on declining if concerned bodies do not take sound full actions. The government should take the responsibilities of creating awareness within the community, incorporate the issue in its development plans and programs, encourage non-governmental organizations to incorporate environmental protection activities in their programs. The heavier load, however, is levied on the shoulder of the community to avert the upcoming worse events in connection with this precious and indispensable resource.
 - Environmental change detection using remote sensing and GIS techniques in the entire Omo-Gibe Basin help facilitate the actions to be taken.
 - Streams gauging instruments should be installed at the mouth of the Weybo River catchment that greatly help reduce the uncertainties arising from projection of flow rates from analogue catchments
 - Groundwater level change assessments for the existing groundwater sources have to be carried out.

- In order to effect the application of chloride mass balance in groundwater recharge estimation, measurements of concentration of chloride in precipitation in a multi-year series has to be made and the chloride concentration in the unsaturated soil zone should be precisely measured at different seasons.
- Major ion chemistry analysis should be done for river water samples to show their interaction with the groundwater system.
- Soil and land-use-land-cover maps should be produced for the study area.
- To enhance the management and evaluation of surface and groundwater resources, the meteorological service authority and the ministry of water resources, are suggested to collect reliable data on daily basis.
- Prior to conduct pumping test, existence of nearby boreholes should be assessed, and if there exists within the anticipated area of influence, draw down measurements would better be taken.
- Observation pipes should be installed in the existing and newly constructed boreholes.
- Borehole sitting should focus on the identification and mapping of fractures traces than on the intensity of weathering.
- High yielding springs should exhaustively be utilized prior to conducting drilling of deep boreholes.
- Lateral inhomogeneity hunting (profiling) of geophysical technique has to be conducted across inferred faults and the known fault to confirm their existence and estimate their depth.

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Annex-1 Projected mean river discharge of Weybo River catchment

SUMMARY OF WEYBO RIVER DISCHARGE, m ³ /s, 1992 - 2005													
WAT. YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
1992	0.873	0.742	1.116	2.475	5.521	3.785	5.754	27.050	35.044	34.221	26.519	10.400	
1993	1.235	1.942	0.787	1.907	8.330	7.991	8.415	17.491	11.366	4.984	1.654	0.781	
1994	0.622	0.548	1.014	1.751	3.505	3.776	17.453	27.442	12.739	4.436	1.430	0.713	
1995	0.548	0.557	0.534	3.310	2.833	2.426	11.675	14.278	21.995	11.761	1.996	0.669	
1996	0.569	0.348	1.618	3.855	6.759	30.334	22.546	21.688	28.892	7.230	1.878	0.666	
1997	0.424	0.345	0.528	3.113	3.575	2.152	4.180	5.406	3.001	11.454	18.458	7.985	
1998	2.662	1.598	1.509	2.043	5.394	6.252	14.847	26.248	14.988	16.848	6.432	2.054	
1999	1.318	0.928	1.223	2.302	2.553	2.856	9.367	11.557	10.602	19.428	5.146	1.483	
2000	0.525	0.427	0.545	1.760	4.710	1.509	2.564	7.310	8.012	12.695	6.160	1.556	
2001	0.704	0.542	0.545	1.350	5.071	6.535	13.131	26.761	19.498	12.598	3.060	0.848	
2002	0.878	0.793	1.940	1.350	0.943	0.973	1.512	2.673	2.187	0.843	0.366	0.610	
2003	0.539	0.454	1.630	2.635	0.914	2.043	6.841	20.403	5.671	0.843	0.365	0.628	
2004	0.873	0.742	1.116	2.453	4.051	1.229	3.260	5.208	4.572	5.777	1.129	0.510	
2005	0.448	0.422	1.515	4.032	2.554	1.231	3.259	5.207	4.571	5.778	1.128	0.510	
MEAN	0.873	0.742	1.116	2.453	4.051	5.221	8.915	15.623	13.081	10.636	5.408	2.101	70.219

Annex-3 Hydraulic characteristics of boreholes obtained from well completion reports

Administrative location			Geographic Location			Depth	SWL	Yield	K	T	Aquifer	Aquifer
Zone	Wereda	Kebele	E	N	Elevation	m.b.g.s	m.b.g.s	(L/s)	(m/d)	m ² /day	Formation	Thickness
Welaita	Boloso	Dola	359968	775158	1816	134	39.3	8	0.377	13.5		36
Welaita	Boloso	Dengera Selata	362093	774064	1864	182	69.1	6	0.175	5.68		36
Welaita	Sodo-Zu	Gurumo-K	360947	770598	1932	150	48.1	6	0.363	10.9		30
Hadiya	Konteb	Lera	373000	784600	1880	120	26	5				24
Welaita	Boloso	Dengera	361088	774707	1845	134	62	5.6	0.55	5.6		24
		Areka	357337	780293	1726	160	12.7	3	0.1	1.3		
Welaita	Boloso	Admancho	366299	777862	1869	136	65.2	1.4	0.181	3.914		25
Welaita	Boloso	Gununo	351405	764815	2022	102	34	5.8	0.875	15.72		18
Welaita	Damot Gale	Boditi	374308	770495	1943	97.5	33.25	3.3	0.24	4.34		18
Welaita	Damot Gale	Boditi	373500	769600	2000	143.5	59	4.65	0.425	10.2		24
Hadiya	Bade-wacho	Gere Bulgeta	380200	785400	1890	101	13.5	2				18
Hadiya	Bade-wacho	Kotu	382000	784000	1890	135	61.13	6.2	0.97	20.3		21
Hadiya	Bade-wacho	Kerenso	381500	782000	1880	180	112	14	1.25	18		16
Hadiya	Bade-wacho	Jarso Hadena	376300	784500	1920	103	20.3	1.5	0.08	1.76		18

Annex-4 Ground water sources inventory data
G.W.L. = ground water level below ground surface

Source	Zone	Wereda	Kebele	Village	E	N	Elevation	Depth,m	S.W.L,m	G.W.L. (m)
Bore hole	Welaita	Boloso	Dola	Mehal	359968	775158	1816	134	39.3	1776.7
Borehole	Welaita	Boloso	Dengara	Bobodo	362093	774064	1864	182	69.1	1794.9
Borehole	Welaita	Sodo Zuria	Gurumo	Schl.Com.	360947	770598	1932	150	48.1	1883.9
Borehole	Welaita	Boloso	Dengara medalcho	Mehal Medalcho	361088	774707	1845	134	62	1783
Borehole	Welaita	Boloso	Admancho	Mehal	366299	777862	1869	136	65.2	1803.8
Borehole	Welaita	Boloso	Gununo		351405	764815	2022	102	34	1988
Borehole	Welaita	Boloso	Areka		357337	780293	1726	160	12.7	1713.3
Borehole	Welaita	Damot Gale	Boditi	Doge	374308	770495	1943	97.5	33.25	1909.75
Borehole	Welaita	Damot Gale	Boditi	Kera	373500	769600	2000	143.5	59	1941
Borehole	Hadiya	Bade-wacho	Gere-Bulgeta		380200	785400	1890	101	13.5	1876.5
Borehole	Hadiya	Badewacho	Kotu		382000	784000	1890	135	61.13	1829
Borehole	Hadiya	Badewacho	Kerenso		381500	782000	1880	180	112	1768
Borehole	Hadiya	Bade-wacho	Jarso Hadenana		376300	784500	1920	103	20.3	1900
Borehole	Hadiya	Konteb	Lera		373000	784600	1880	120	26	1854
Borehole	Welaita	Boloso	Legama	Ziga	361735	778403	1820	55.9	35.1	1784
Borehole	Welaita	Boloso	Legama	Ziga	361011	777272	1833	75	49	1784
Borehole	Welaita	Boloso	Yukera		356921	773725	1872	92.5	80	1782
Borehole	Welaita	Boloso	Ambe		342174	786464	1460	25.5	13.5	1446.5
Borehole	Welaita	Boloso	Ambe		341034	788885	1490	61.7	41.4	1448.6
Zone	Wereda	Kebele	Village	E	N	Elevation				
Borehole	Welaita	Boloso	Weybo		356223	778940	1800	68.5	39	1761
Borehole	Welaita	Boloso	Weybo		354447	774853	1891	84	53.2	1837.8
Borehole	Welaita	Boloso	Tedisa		359849	779001	1772	34.5	14.4	1757.6
Spring	Welaita	Boloso	Anchucho	Mere	355047	769297	1907			1907
Spring	Welaita	Boloso	Gununo	Tekacha	350715	764395	2025			2025
Spring	Welaita	Boloso	Sorehomba	Watere	353901	783084	1738			1738
Spring	Welaita	Boloso	Afamabanc	Tilikie	349852	782634	1760			1760
Spring	Welaita	Boloso	Afamabanc	Adila	351180	782050	1763			1763
Spring	Welaita	Boloso	Basa	Unchema	364000	784480	1798			1798
Spring	Welaita	Boloso	Yukera	Killo	356104	777874	1753			1753
Spring	Welaita	Boloso	Weybo	Mun-awa	354196	776681	1810			1810
Spring	Welaita	Boloso	Bedaye	Edicho	337736	788443	1412			1412
Spring	Welaita	Boloso	Omo-Bedaye	Kirko(Meselalo)	355686	789265	1317			1317
Spring	Welaita	Boloso	Sunkelle	Koisha	356327	771763	1882			1882
Spring	Welaita	Boloso	Shaymba	Takacha	354816	765345	1987			1987
Spring	Welaita	Boloso	Gununo	Woisha	352242	768316	1968			1968
Spring	Welaita	Boloso	Gununo	Esie	352180	768153	1972			1972
Spring	Welaita	Boloso	Afamino	Fulasa	351373	777704	1881			1881
Spring	Welaita	Boloso	Dembazami	Tulame	351378	772741	1910			1910
Spring	Welaita	Boloso	Afamino	Kaei	350541	773576	1939			1939
Spring	Welaita	Boloso	Ambe	Chena	340823	786738	1429			1429
Spring	Welaita	Boloso	Bombe	Megara	344085	790880	1486			1486
Spring	Welaita	Boloso	Adilla	Gereje	347050	789803	1523			1523

Spring	Welaita	Boloso	Adilla	Dodola	347957	788541	1605			1605
	Zone	Wereda	Kebele	Village	E	N	Elevation			
Spring	Welaita	Boloso	Dola	Mehal	359968	775158	1816	134	39.3	1776.7
Spring	Welaita	Boloso	Tedisa	Bara - 1	359510	780410	1719			1719
Spring	Welaita	Boloso	Tedisa	Bara - 2	359195	780685	1728			1728
Spring	Welaita	Boloso	Tedisa	Bara - 3	359317	780779	1724			1724
Spring	Welaita	Boloso	Areka	Kulle	356889	780427	1731			1731
Spring	Hadiya	Badewacho	Shapa		369541	784530	1857			1857
Spring	Hadiya	Badewacho	Shapa		369412	784508	1853			1853
Spring	Welaita	Boloso	Dolla	Larcha	359098	777489	1750			1750
Spring	Welaita	Boloso	Bedaye	Edicho	335445	789195	1305			1305
Spring	Welaita	Boloso	Dubo	Marana	355675	780544	1750			1750
Spring	Welaita	Boloso	Gidohomba	Shuye	352066	786887	1691			1691
Spring	Welaita	Boloso	Gidohomba	Kuto Zone	349633	789586	1595			1595
Spring	Welaita	Boloso	Weybo	Anka	355563	776893	1795			1795
Spring	Welaita	Boloso	Weybo	Zone-1	353800	778000	1800			1800
Spring	Welaita	Boloso	GaraGodo	Wadu	362708	781536	1761			1761
Spring	Welaita	Boloso	Achura	Ajacho	355219	790644	1761			1761
Spring	Welaita	Boloso	Dubo	Etana	353730	780545	1781			1781
Spring	Welaita	Boloso	Tadisa	Lei	358926	780800	1716			1716
Spring	Welaita	Boloso	Weybo	Zone-7	352872	775011	1851			1851
Hand Dug	Welaita	Boloso	Sorehomba	Sedancho	352314	780203	1848	15	11	1837
Hand Dug	Welaita	Boloso	Afamabanchi	Adifa Zone	351106	782920	1782	19	16	1766
Hand Dug	Welaita	Boloso	Imbicho	Dino Mahidi	352335	790170	1686	13.5	6	1680
Hand Dug	Welaita	Boloso	Basa Gofera	Newasie	360509	784339	1748	12	8	1740
	Zone	Wereda	Kebele	Village	E	N	Elevation			
Hand Dug	Welaita	Boloso	GaraGodo	ChalaZone	365440	784301	1830	16	15	1815
Hand Dug	Welaita	Boloso	Dache Gofera	Mehal Dache	367910	783195	1856	19	14.5	1841.5
Hand Dug	Welaita	Boloso	Dache Gofera	Male Zone	367254	782585	1861	19	15	1846
Hand Dug	Welaita	Boloso	Dembazamine	Weraza	350265	768819	1984	24	22	1962
Hand Dug	Welaita	Boloso	Dembazamine	Boko-1	350912	769714	1972	17.5	3	1969
Hand Dug	Welaita	Boloso	Weybo	Zone-5	354869	776924	1838	11.5	10	1828
Hand Dug	Welaita	Boloso	Ajora	Semine	344490	792387	1545	17.5	16	1529
Hand Dug	Welaita	Boloso	Tedisa	Wargo	359696	779331	1823	20	15	1805
Hand Dug	Welaita	Boloso	Shiamba	Takacha	352970	765750	2015	13	6	2009
Hand Dug	Welaita	Boloso	Dubo	Bergia	355883	784306	1747	16	11	1736
Hand Dug	Welaita	Boloso	Weybo	Zone-1	354786	778952	1831	20	19	1812
Hand Dug	Welaita	Boloso	Farawocha	Odoro	346247	788622	1604			
Hand Dug	Welaita	Boloso	Sorehomba	Offa	352913	780899	1824	19	16	1808
Hand Dug	Welaita	Boloso	Adilla	Koishe	348800	787895	1666	17	16	1650
Hand Dug	Welaita	Boloso	Dengera	Hatawocha	364391	774591	1899	21	20	1879
Hand Dug	Welaita	Boloso	Dola	ArekaDola	358710	777204	1807	29	27	1780
Hand Dug	Welaita	Boloso	Arfita	Admancho	366583	778524	1869	11	10	1859
Hand Dug	Welaita	Boloso	Dache	Ulbo Zone	369548	782538	1760	18	17	1743
Hand Dug	Welaita	Boloso	Dubo	Suta	355032	782589	1785	21	20	1765
Hand Dug	Welaita	Boloso	Weybo	Zone-2	355526	778454	1810	12.5	12	1798
Hand Dug	Welaita	Boloso	Dubo	Meshido	356039	779924	1768	21.5	19	1749

	Zone	Wereda	Kebele	Village	E	N	Elevation			
Hand Dug	Welaita	Boloso	Dubo	Zone-5	356623	779846	1757	16	14	1743
Hand Dug	Welaita	Boloso	Dubo	Meshido	356544	779622	1766	12	10	1756
Hand Dug	Welaita	Boloso	Weybo	Zone-4	355704	778334	1812	21	20	1792
Hand Dug	Welaita	Boloso	Tedisa	Wargo	359277	778963	2075	16	15	2060
Hand Dug	Welaita	Boloso	Tedisa	Lei-Zone	358569	780665	1734	18	16.5	1717.5
Hand Dug	Welaita	Boloso	Areka	town	357867	780874	1731	10	9	1722
Hand Dug	Welaita	Boloso	Dubo	Suta	355011	782546	1785	11	10	1775
Hand Dug	Welaita	Boloso	Gidohomba	Ketena-3	352605	785179	1735	14	12	1723
Hand Dug	Welaita	Boloso	Gidohomba	Ketena-3	352380	785457	1719	10	9	1710
Hand Dug	Welaita	Boloso	Gidohomba	Shuye Zone	352142	785488	1710	16	10	1700
Hand Dug	Welaita	Boloso	Gidohomba	Shuye Zone	351561	787160	1692	20	15	1677
Hand Dug	Welaita	Boloso	Adilla	Chema	348955	788567	1663	10	6	1657
Hand Dug	Welaita	Boloso	Wermuma	Betale	358649	785074	1729	16.5	15	1714
Hand Dug	Welaita	Boloso	Basa	Newasie	362166	783390	1776	9	7	1769
Hand Dug	Welaita	Boloso	GaraGodo	Hago	363518	782261	1821	20	18.5	1801.5
Hand Dug	Welaita	Boloso	GaraGodo	Hago	364962	782498	1826	20	18	1808
Hand Dug	Welaita	Boloso	Admancho	Arfita Sukie	365622	780237	1804	10	9.5	1794.5
Hand Dug	Welaita	Boloso	Achura	Sefera	356568	790910	1707	42	30	1677
Hand Dug	Welaita	Boloso	Anchucho	Genda	353906	770325	1950	9	8	1942

Annex-5 HCA-Clustered water samples

	Source	ID	Site	E	N	Na	K	Ca	Mg	HCO ₃	SO ₄	Cl	TDS	Ph	EC
Sub-group-1	Han Dug	DW-1	Ajora	344490	792387	1.468	0.134	0.479	0.158	0.96	0.079	0.423	77	7.6	153.9
	Han Dug	DW-6	Weybo	354869	776924	2.503	0.269	0.319	0.237	1.2	0.283	0.352	97.4	8	194.3
	Han Dug	DW-8	Garagodo	365440	784301	0.952	0.166	0.798	0.395	1.2	0.054	0.535	100	7.3	200
	Spring	CS-8	Dembaza	351378	772741	1.169	0.02	0.4	0.4	0.7	0.312	0.282	38.2	7.1	77
Mean						1.523	0.147	0.499	0.298	1.015	0.182	0.398	78.15	7.5	156.3

Sub-group-2	Spring	CS-4	Gamowal	349806	784746	0.946	0.038	0.52	0.28	1.52	0.004	0.141	69.9	7.75	142.5	
	Rain	R	Areka			0.033	0.032	0.399	0.198	0.48	0.015	0.07	20.1	7	40.2	
	Spring	CS-5	Afama	349852	782634	0.146	0.134	0.639	0.553	0.72	0.14	0.282	54.9	7	109.5	
	Spring	CS-6	Gununo	350715	764395	0.481	0.07	0.2	0.296	0.6	0.027	0.169	28.9	7.5	57.8	
	Spring	CS-7	Afama	351170	782026	0.96	0.036	0.68	0.24	1.7	0.087	0.085	78.3	7.35	157.2	
	Spring	CS-9	Gununo	352430	768427	0.879	0.026	0.4	0.4	0.62	0.123	0.353	63.8	7.5	126.5	
	Spring	CS-10	Weybo	354196	776681	1.535	0.128	0.359	0.237	1.4	0.217	0.225	45.1	7.5	90	
	Spring	CS-11	Sunkelle	355026	769311	0.805	0.122	0.399	0.395	1.5	0.044	0.07	28.3	7.2	56.2	
	Spring	CS-13	Gununo	359392	765632	0.466	0.102	0.639	0.553	1.2	0.067	0.141	59.1	7.2	118.1	
	Borehole	BH-10	Chewkere	355047	769297	0.169	0.154	0.798	0.593	1.4	0.077	0.056	28.3	7.2	56.2	
	Han Dug	DW-3	Afama	351106	782920	0.746	0.102	0.878	0.316	1.6	0	0.099	54.9	7	109.5	
	Han Dug	DW-4	Imbecho	352335	790170	1.008	0.125	0.16	0.119	0.7	0.075	0.225	38.4	7.9	76.6	
	Han Dug	DW-5	Shiamba	352970	765750	0.096	0.154	0.319	0.474	0.5	0.056	0.211	25.3	7.6	50.6	
	Mean						0.01	0.12	0.54	0.37	1.13	1.75	0.75	51.28	7.39	95.89

Sub-group-3	Borehole	BH-15	Dengera	361028	774707	0.308	0.051	2.2	1.48	3.8	0	0.127	210	7.3	410
	Han Dug	DW-9	Dache	369548	782538	3.705	0.054	3	1	7.52	0	0.085	309	7.6	618
Mean						2.006	0.052	2.6	1.24	5.66	0	0.106	259.5	7.45	514

Sub-group-4	Borehole	BH-4	Farawocha	346590	789976	2.82	0.256	0.599	1.146	3.699	0	0.085	180	8.2	360
	Borehole	BH-5	Gununo	351405	764815	1.529	0.077	0.539	0.214	1.344	0	0.118	103	5.96	150
	Borehole	BH-7	Sorehomba	353200	782733	1.017	0.198	0.798	0.099	1.8	0.054	0.113	112.5	7.8	225
	Borehole	BH-12	Tedisa	359849	779001	1.651	0.186	0.798	0.474	2.899	0	0.141	105	7.4	175
	Borehole	BH-13	Dengera Selat	360056	775363	1.923	0.179	0.68	0.32	2.72	0	0.113	130	7.1	260
	Han Dug	DW-2	Dembaza	350912	769714	1.384	0.352	2.395	0.198	2.919	0	0.127	146	7.4	292
	Han Dug	DW-7	Weybo	355709	778332	1.299	0.262	0.24	0.553	1.8	0.098	0.211	103.4	7.2	207
	Spring	CS-3	Adila	347498	789321	3.269	0.054	0.64	0.52	3.42	0.021	0.085	190	8.36	380
Mean						1.861	0.195	0.836	0.44	2.575	0.022	0.124	133.7	7.428	256.1

Sub-group-5	Borehole	BH-1	Ambe	341031	788885	2.118	0.046	1.198	1.185	4.199	0	0.07	185	7.3	306
	Borehole	BH-2	Ambe	342174	786464	2.837	0.036	0.798	0.79	3.999	0.048	0.211	105	6.9	176
	Borehole	BH-3	Bombe	343896	787410	0.966	0.033	0.52	0.48	1.9	0.002	0.071	180	7.7	330
	Borehole	BH-6	Sorehomba	353127	782509	1.364	0.031	1.08	0.12	2.4	0	0.042	41.7	6.6	84.5
	Borehole	BH-8	Sorehomba	353589	784109	0.923	0.033	0.28	0.24	1.4	0	0.056	190	6.8	360
	Borehole	BH-9	Weybo	354546	776252	1.797	0.038	0.798	0.592	2.999	0	0.07	121	7	201
	Borehole	BH-11	Wermuma	358151	785304	1.825	0.038	0.6	0.6	2.88	0	0.071	126	7.5	252
	Borehole	BH-14	Legama	361014	777267	1.467	0.038	0.798	0.395	2.599	0.013	0.028	119	7.1	198
	Borehole	BH-16	Legama	361734	778403	1.186	0.031	1.397	0.198	2.599	0.027	0.042	113	7	189
	Borehole	BH-17	Dengara	362093	774064	1.074	0.041	0.4	0.4	1.48	0.006	0.212	140	7.4	280
	Borehole	BH-18	Admancho	365269	777916	1.55	0.036	1.12	0.68	3.2	0.008	0.071	133	7.4	264
	Spring	CS-1	Ambe	340823	786738	0.962	0.038	1.56	0.68	3.04	0.033	0.071	81.2	8.12	163.7
	Spring	CS-12	Achura	355235	790683	1.073	0.041	1.8	0.6	2.96	0.035	0.099	67.6	8	135
	Spring	CS-14	Tedisa	359620	781220	2.108	0.041	0.56	0.56	2.8	0.106	0.099	124	7.5	248
Mean						1.518	0.037	0.922	0.537	2.747	0.02	0.087	123.3	7.309	227.7

Annex-6 In-situ and laboratory measured water chemistry parameters

	Source	Kebele	Village	E	N	Elevation	Cl ⁻	Na ⁺	K ⁺	Ca ⁺⁺	Mg ⁺⁺	HCO3 ²⁻	NO3 ⁻¹	SO4 ⁻²	PO4 ⁻³	Total alkal	TDS	pH	EC
1	Rain	Areka		357300	781000	1750	0.070	0.033	0.032	0.399	0.198	0.480	0.135	0.015	0.003	24	20.1	7	40.2
2	Borehole	Sorehomba		353127	782509	1792	0.0423	1.3636	0.0306	1.08	0.12	2.4	0.1065	0	0.0118	120	41.7	6.6	84.5
3	Borehole	Sorehomba		353589	784109	1768	0.0564	0.9232	0.0332	0.28	0.24	1.4	0.0567	0	0.021	70	190	6.8	360
4	Borehole	Dengera	medalcho	361028	774707	1845	0.1269	0.3078	0.051	2.2	1.48	3.8	0.0709	0	0.0267	190	210	7.3	410
5	Borehole	Dengara Selata	Bobodo	362093	774064	1864	0.2115	1.0742	0.0409	0.4	0.4	1.48	0.0567	0.0062	0.0631	74	140	7.4	280
6	Borehole	Bombe		343896	787410	1528	0.0705	0.9657	0.0332	0.52	0.48	1.9	0.0851	0.002	0.0134	95	180	7.7	330
7	Borehole	Wermuma		358151	785304	1725	0.0705	1.8249	0.0383	0.6	0.6	2.88	0	0	0.1107	149	126	7.5	252
8	Borehole	Admancho Arfit	Anka	365269	777916	1845	0.0705	1.5495	0.0358	1.12	0.68	3.2	0.0425	0.0083	0.0555	160	133	7.4	264
9	Borehole	Legama	Ziga-02	361014	777267	1828	0.0282	1.4668	0.0384	0.7984	0.395	2.599	0.0497	0.0125	0.0255	130	119	7.1	198
10	Borehole	Legama	Ziga-01	361734	778403	1820	0.0423	1.1858	0.0307	1.397	0.198	2.599	0.0781	0.0271	0.0221	130	113	7	189
11	Borehole	Tedisa	Kendama	359849	779001	1772	0.1408	1.6513	0.1855	0.7984	0.474	2.8994	0.0568	0	0.122	145	105	7.4	175
12	Borehole	Ambe		342174	786464	1460	0.2113	2.8372	0.0358	0.798	0.79	3.999	0.2555	0.0479	0.073	200	105	6.9	176
13	Borehole	Ambe	Kuto	341031	788885	1479	0.0704	2.118	0.046	1.198	1.185	4.199	0	0	0.0053	135	185	7.3	306
14	Borehole	Weybo		354546	776252	1866	0.0704	1.797	0.0384	0.798	0.592	2.999	0.0355	0	0.0643	150	121	7	201
15	Borehole	Gununo		351405	764815	2022	0.118	1.529	0.077	0.539	0.214	1.344					103	5.96	150
16	Borehole	Dengera Selata		360056	775363	1832	0.1128	1.9233	0.179	0.68	0.32	2.72	0.1348	0	0.0113	136	130	7.1	260
17	Borehole	Sorehomba		353200	782733	1888	0.1127	1.0165	0.1982	0.7984	0.0987	1.7996	0.1774	0.0541	0.0049	90	112.5	7.8	225
18	Borehole	Farawocha		346590	789976	1543	0.0845	2.8197	0.2558	0.5988	1.1455	3.6992	0.1845	0	0.0099	225	180	8.2	360
19	Borehole	Chewkere	Mere	355047	769297	1907	0.0563	0.1693	0.1535	0.7984	0.5925	1.3997	0.2129	0.077	0.0041	70	28.3	7.2	56.2
20	Spring	Gamowalena	Borosa	349806	784746	1682	0.141	0.9455	0.0383	0.52	0.28	1.52	0.1064	0.0041	0.0186	76	69.9	7.75	142.51
21	Spring	Afamabanchi	Adila	351170	782026	1781	0.0846	0.9598	0.0358	0.68	0.24	1.7	0.2981	0.0874	0.0041	106	78.3	7.35	157.2
22	Spring	Tedisa	Bara	359620	781220	1726	0.0987	2.1075	0.0409	0.56	0.56	2.8	0.1774	0.1061	0.0947	140	124	7.5	248
23	Spring	Ajora	Chena	344576	797305	1451	0.0987	0.9778	0.0225	0.4	0.4	1.36	0.2838	0	0.0442	68	67	7.6	135.7
24	Spring	Ambe	Male	340823	786738	1429	0.0705	0.9619	0.0383	1.56	0.68	3.04	0.078	0.0333	0.0266	152	81.2	8.12	163.7
25	Spring	Adila	Gereje	347498	789321	1557	0.0846	3.2685	0.0537	0.64	0.52	3.42	0.0561	0.0208	0.0226	215	190	8.36	380
26	Spring	Achura	Mokota	355235	790683	1639	0.0987	1.0728	0.0409	1.8	0.6	2.96	0.1348	0.0353	0.0291	148	67.6	8	135
27	Spring	Gununo		352430	768427	1988	0.3526	0.879	0.0255	0.4	0.4	0.62	0.7168	0.1228	0.0125	31	63.8	7.5	126.5

28	Spring	Dembazamine	Tulame	351378	772741	1910	0.2821	1.1693	0.0204	0.4	0.4	0.7	0.7821	0.3123	0.0347	35	38.2	7.1	77
29	Spring	Weybo	Mun-awa	354196	776681	1810	0.2254	1.5351	0.1279	0.3593	0.237	1.3997	0.7239	0.2165	0.0148	70	45.1	7.5	90
30	Spring	Gununo	Mentere	359392	765632	1945	0.141	0.4657	0.1023	0.6387	0.553	1.1997	0.3832	0.0666	0.0075	60	59.1	7.2	118.1
31	Spring	Afamabanchi	Adila	349852	782634	1760	0.2817	0.1458	0.1343	0.6387	0.553	0.7198	0.6033	0.1395	0.009	36	54.9	7	109.5
32	Spring	Gununo		350715	764395	2025	0.169	0.4809	0.0703	0.1996	0.2962	0.5999	0.2697	0.0271	0.0024	30	28.9	7.5	57.8
33	Spring	Weybo	Anka	355612	776615	1795	0.1972	2.2587	0.1535	0.2794	0.1185	1.7996	0.7097	0.1291	0.0186	90		6.0	1
34	Spring	Areka	Kule	356887	780418	1728	0.1408	2.1805	0.1279	0.3992	0.1975	2.3995	0.2697	0.0562	0.0227	120		6.2	
35	Spring	Sorehomba	Bunabord	353901	783084	1738	0.704	1.4198	0.0831	0.1796	0.0197	0.5999	0.3213	0.075	0.0019	32		5.8	
36	Spring	Gidohomba	Kuto	349633	789586	1595	0.0704		0.1919	0.3593	0.3555	2.2995	0.0852	0	0.0085	115		6.3	1
38	Spring	Tedisa	Lei	358926	780800	1716	0.1197	1.284	0.1407	0.3194	0.0079	1.3997	0.2768	0.0583	0.006	70		6.2	1
39	Spring	Sunkelle	Mere	355026	769311	1955	0.0704	0.8045	0.1215	0.3992	0.395	1.4997	0.1277	0.0437	0.0068	75	28.3	7.2	56.2
40	Hand Dug Well	Dache Gofera		369548	782538	1760	0.0846	3.7046	0.0537	3	1	7.52	0.0425	0	0.0676	376	309	7.6	618
41	Hand Dug Well	Afamabanchi	Adila	351106	782920	1782	0.0986	0.7458	0.1023	0.8782	0.316	1.5997	0.3832	0	0.086	80	54.9	7	109.5
42	Hand Dug Well	Ajora	Semine	344490	792387	1479	0.4225	1.4675	0.1343	0.479	0.158	0.9598	0.8375	0.0791	0.0137	48	77	7.6	153.9
43	Hand Dug Well	Weybo	Zone-5	354869	776924	1838	0.3521	2.5031	0.2686	0.3194	0.237	1.1997	1.9446	0.2832	0.0202	60	97.4	8	194.3
44	Hand Dug Well	Dembazamine	Boko	350912	769714	1972	0.1268	1.3838	0.3517	2.3952	0.1975	2.9194	0.2839	0	0.0099	196	146	7.4	292
45	Hand Dug Well	Garagodo	Chala	365440	784301	1830	0.5352	0.9521	0.1663	0.7984	0.395	1.1997	0.8517	0.0541	0.0067	60	100	7.3	200
46	Hand Dug Well	Imbecho		352335	790170	1686	0.2254	1.008	0.1251	0.1597	0.1185	0.6999	0.5039	0.075	0.0061	35	38.4	7.9	76.6
47	Hand Dug Well	Shiamba		352970	765750	2015	0.2113	0.0961	0.1535	0.3194	0.474	0.4999	0.3478	0.0562	0.0047	25	25.3	7.6	50.6
48	Hand Dug Well	Weybo	Eltikerie	355709	778332	1809	0.2113	1.2991	0.2622	0.2395	0.553	1.7996	0.3194	0.0979	0.0083	90	103.4	7.2	207
49	Hand Dug Well	Gidohomba	Ketena-3	352605	785517	1735	0.0986	0.6583	0.1727	0.3988	0.0395	1.3037	0.0994	0.0708	0.0112	65.2		6.2	7