

ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES
DEPARTMENT OF EARTH SCIENCES



**GROUNDWATER POTENTIAL EVALUATION AND FLOW DYNAMICS OF
HORMAT-GOLINA RIVER CATCHMENT, KOBO VALLEY, NORTHERN ETHIOPIA**

BY

Afewerk Desalegn

*A Thesis Submitted to the School of Graduate Studies of Addis Ababa University In
Partial Fulfillment of the Requirements for the Degree of Master of Science in
Hydrogeology.*

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ABSTRACT

The study aims to describe and give some detailed picture on the Hydrogeological features of the Hormat- Golina basin with more focus on the flat areas of the Kobo valley. This makes an interest from the groundwater potential point of view to evaluate its water resource potential on the basis of aquifer characterization, recharge mechanism, groundwater flow conditions and hydrochemistry of the groundwater. The basin is part of the western escarpment of Afar Rift and measures about 806 km² areas. It is situated between 545000 to 581000m East longitude and 1315000 to 1351000m North latitude with an average elevation of 1482m.a.s.l and 2605m.a.s.l for the valley and highland part of basin, respectively. The average monthly temperature and the mean annual precipitation in the valley are 22.4^oC and 739mm, respectively. Potential evapotranspiration (PET) of the valley was estimated using Penman Combination method which gives annual PET value of 1596.1mm/y. Actual evapotranspiration value for the catchment estimated from Turc method gives value of 655mm. The annual surface water out flow, estimated using runoff coefficient methods resulted 98.4MCM. Chloride mass balance (CMB) method, Darcy and conventional water balance approaches were used to estimate recharge, while the average of the three values is taken as the annual recharge of the area (44.8MCM/year) which is 6.4% of the total precipitation and groundwater reserve of the valley is estimated as 2033MCM. To characterize the aquifer system of the area pumping test data, well completion reports, well logs and geology of the area were analyzed. The study area is characterized by deep groundwater systems encountered at an average depth of 141m. Their hydraulic characteristics are spatially variable, which the transmissivity of the valley ranges from 6.85 – 4510 m²/d and the mean, and median are 492.38 m²/d, and 199m²/d, respectively. Its hydraulic conductivity ranges from 0.19 – 125 m/d and the mean, and median are 10.9 m/d, and 4.25m/d, respectively. The Quaternary unconsolidated sediments are the main aquifer units in the area. These aquifers were found to be good groundwater potential zone. The general trend for groundwater flow observed from pieziometric heads is from western highland part of the area towards the plain in the direction of west to east of the study area. Piper plots, Collins bar diagram and Hierarchical cluster Analysis (HCA) were used to classify the water chemistry. Groundwater type of the area was evolved from Ca-Mg-HCO₃ or Mg-Ca-HCO₃ water type in the area closer to western escarpment in to Na-Ca-HCO₃ water type in the eastern tip of the area. The water also was of a low sodium hazard and can therefore be used for irrigation without posing much risk to the compaction of soils.

Key word: Kobo valley, groundwater potential, recharges estimation, hydrochemistry.

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Acronyms

AET	Actual Evapo-transpiration
CMB	Chloride Mass Balance
Co-SAERAR	Commission for Sustainable Agriculture and Environmental Rehabilitation in Amhara Region
d	Days
DEM	Digital Elevation Model
EC	Electrical Conductivity
EIGS	Ethiopian Institute of Geological Survey
ETo	Potential Evapotranspiration
E-W, S-N	East-West, South-North
FAO	Food and Agriculture Organization
GES	Geo-Engineering Service
GPS	Geographic Positioning System
HCA	Hierarchical cluster analysis
ITCZ	Inter-Tropical Convergence Zone
KGVDP	Kobo-Girana Valley Development Project
m.a.s.l	Meter above sea level
MCM	Million Cubic Meters
My	Million years
ORDA	Organization for Rehabilitation and Development in Amhara
PET	Potential Evapo-transpiration
RVDP	Raya Valley Development Project
SAR	Sodium Absorption Ratio
SCS	Soil Conservation Service
SMD	Soil moisture deficit
SWL	Static Water Level
TDS	Total Dissolved Solid
UTM	Universal Transverse Mercator
VES	Vertical Electric Sounding
WHO	World Health Organization
y	Year

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CHAPTER ONE

1. INTRODUCTION

1.1. BACKGROUND

Ethiopia is one of the most drought prone countries in the world, with a significant proportion of the net gross domestic product dependent on rain fed agricultural practices. The intensity and duration of rainfall is highly erratic and variable, resulting in significant reductions in agricultural production and in some cases total crop failure.

The study area of this research is Kobo Valley catchment, situated south of Raya Valley in Northern part of Ethiopia. The annual amount of rainfall is relatively small and erratic as compared to other parts of the country. In addition the area is being affected by a recurrent drought. Due to these facts most of the rivers are intermittent. This makes groundwater to be a better option for water supply and irrigation practices. In addition, the recent intensive fertilizer usage practice in the extension program will endanger the quality of the groundwater in the region. The knowledge of water resources is one of the vital factors in planning and management. Therefore, the study generally focuses of and incorporated water balance to estimate recharge condition, aquifer characterization, evaluation of groundwater potential, groundwater flow and evaluation of hydrochemistry.

1.2. OBJECTIVE

1.2.1. GENERAL OBJECTIVE

The major objective of the research is to describe and give some detailed picture on the Hydrogeological features with more focus on the flat areas or Kobo valley. This makes an interest from the groundwater potential point of view to evaluate its water resource potential on the basis of aquifer characterization, recharge mechanism, groundwater flow conditions and the hydrochemistry of the groundwater.

1.2.2. SPECIFIC OBJECTIVES

The specific objective of this research includes:

- To describe and characterize the major aquifer systems and units in the area;
- Defining mechanism of groundwater recharge and discharge condition;
- Determining the amount of water recharging the groundwater system using different technique;

- To determine the aquifer hydraulic parameter;
- Determination of the storage capacity of the aquifer in the basin;
- To classify the groundwater hydrogeochemically;
- To evaluate water quality from domestic and agricultural point of view;
- To prepare Hydrogeological, depth to groundwater, groundwater quality etc., map of the area.

1.3. APPROACH AND METHODOLOGY

The approach to achieve the objective of the research would involve the following conventional methods with tuning of the basic interest of the work.

1.3.1. PRE-FIELD WORK

In this phase different works were executed:

- ❖ Literature review of all existing reports, maps, and relevant data;
- ❖ Previous works and data were collected from different offices (Ministry of Water Resources, Metaferia Consulting Engineers, Ethiopian Geological Survey, Tana drilling, and China Geo Engineering, Meteorological Agency, and Regional, Zonal and Woreda water Resource development offices);
- ❖ Obtaining DEM and satellite imagery,
- ❖ Base map preparation (Extraction of the surface water divide and preparation of drainage map of the study area from DEM using Arc GIS 9.3 software)

1.3.2. FIELD WORK

- ❖ Confirmation of all the collected data in the pre-field work;
- ❖ Collection of secondary data from different sources and primary data from the study area. The primary data includes, measuring groundwater levels, taking readings of borehole locations and elevation, Discharge of springs was measured wherever possible ;
- ❖ Sampling of water from representative water point and from different source springs, hand dug wells, shallow wells, and boreholes;
- ❖ In situ analysis of the water samples (PH, EC, TDS, and Temperature);
- ❖ Observation of hydrogeological features and description of geology, geomorphologic setting, surface water divide, land covers, land use practices, and location of recharge and discharge areas;
- ❖ Identification of perennial and intermittent stream and spring;

- ❖ The secondary data such as borehole logs, pumping test data, hydrogeochemical data, geophysical data and hydrogeology feasibility report and well completion report were collected from Kobo-Girana Valley Development Project Office (KGVDP).

1.3.3. POST FIELD WORK

This was the main phase of the research work and it includes:

- ❖ Characterization of the metrological elements within and the surrounding of the study area;
- ❖ Interpretation of the satellite imagery of the study area with appropriate resolution;
- ❖ Characterization of geological, hydrological, hydrogeological, and structural condition of the study area based on the existing data;
- ❖ Data organization, processing, analysis and interpretations of pumping test, geophysical and borehole lithological data using different softwares for characterizing the aquifer (determining type, thickness, depth, and interconnection of layers as well as its lateral extent (continuity));
- ❖ Laboratory analysis of water samples collected from field;
- ❖ water chemistry analysis results were collected from secondary and primary sources used for hydrochemical investigation and water chemistry assessment from domestic and agricultural point of view;
- ❖ Organizing, analyzing, and interpreting the primary data were collected; Different software were employed for the preliminary image processing and final analysis these were AquiferTest v3.5, Arc GIS 9.3, Global Mapper 7, Surfer 8, Aquachem 4.0, and Microsoft office Excel 2003 and 2007. For geo referencing of some places and borehole locations Garmin GPS was used.
- ❖ Finally, analyses and interpretations were conduct on the geological, hydrogeological, hydrogeochemical, borehole and geophysical data gathered both as secondary and primary data to evaluate the groundwater potential.

1.4. SIGNIFICANCE OF THE STUDY

The result of this research work will have a great importance in filling the scientific gap, providing detailed Hydrogeological information about the area which can be one input for understanding of hydrogeological systems of the area, and used as data for further research work.

The generated, collected and digitized data has been organized into the logical groups of entities concerning Geological Factors, Hydrological Factor, Hydrogeological Factors and Physiographic Factor to produce properly organized *Geodatabase* which will enable the responsible officers to make decision and review by concerned stakeholders and subsequent researchers.

Moreover, the findings of this research work may be used for understanding the water budget of the basin, this study has substantial importance to utilize the resources safely without harming, provide information in order to utilize the water resources of the area properly and keep the existence of the resources sustainable, for economic feasibility, construction, and development of water supply schemes in the area.

1.5. REVIEW OF PREVIOUS WORK

A number of studies were conducted on the physiographic setup, geology, tectonics and groundwater potential at different levels and localities in Kobo valley. The groundwater potential for irrigation at the valley has been the focus since long due to the expected high groundwater potential. Among the major studies conducted in Kobo-Girana valley are the investigations of groundwater potential for multipurpose by Co-SAERAR from 1996 to 1999 and review and appraisal of Hydrogeological studies by Geo-Engineering Service in 2002/3.

Geo Engineering service (GES) study

The Hydrogeological study of GES identified two groundwater sub basins in Kobo valley, which is Waja-Golesha in the northern part and Hormat-Golina in the southern part. The studies further delineate the divide line between the two groundwater basins and identified well fields for groundwater development. The study indicated annual recharge of two groundwater basins to amount 71MCM. Further the study estimated groundwater reserve in the Kobo valley about 4347MCM.

CO-SAERAR study

The study made preliminary estimation of annual recharge capacity of the Kobo, Alawha, Chireti and Gelana sub basins to be 119, 9, 15 & 27MCM, respectively.

EIGS study

Hydrogeological and environmental isotope investigations have been done by Sileshi Mamo from the Geological Survey of Ethiopia (2007), the total dynamic groundwater in the graben sediments estimated to amount 68.9MCM in Kobo valley.

The Germany Consult Study (GCS)

Geological and Hydrogeological study has conducted using Vertical Electrical Sounding (VES), seismic surveys of geophysical methods, with the aid of satellite image (Nasa-ERTS), aerial photograph of 1:25,000 and 1:50,000. The GCS has divided the Kobo-Alamata basins in to different geological blocks. Accordingly, Hormat-Golina block is covered with relatively thick unconsolidated sediments and composed of relatively coarser sedimentary deposits which can be good groundwater reservoirs.

Therefore, following the previous recommendation this study has conducted an exhaustive hydrogeological study with respect to recharge estimation using different techniques, aquifer characteristics, groundwater flow and hydrochemistry of the area.

CHAPTER TWO

2. GENERAL OVER VIEW OF THE STUDY AREA

2.1. LOCATION

The study area is located in Northern part of Ethiopia, North Eastern Amhara regional state, North Wollo Administrative Zone about 580 km north of the capital Addis Ababa. The study area is bounded with UTM Geographic coordinate 1315000m to 1351000m N latitude and 545000m to 581000m E longitude (fig 2.1). It covers a total area of 806km² and named Hormat – Golina basin. It is bounded by highly rugged mountains of Lasta in the west, Zobel Mountains in the east, Raya Valley in the north, and volcanic ridges in the south.

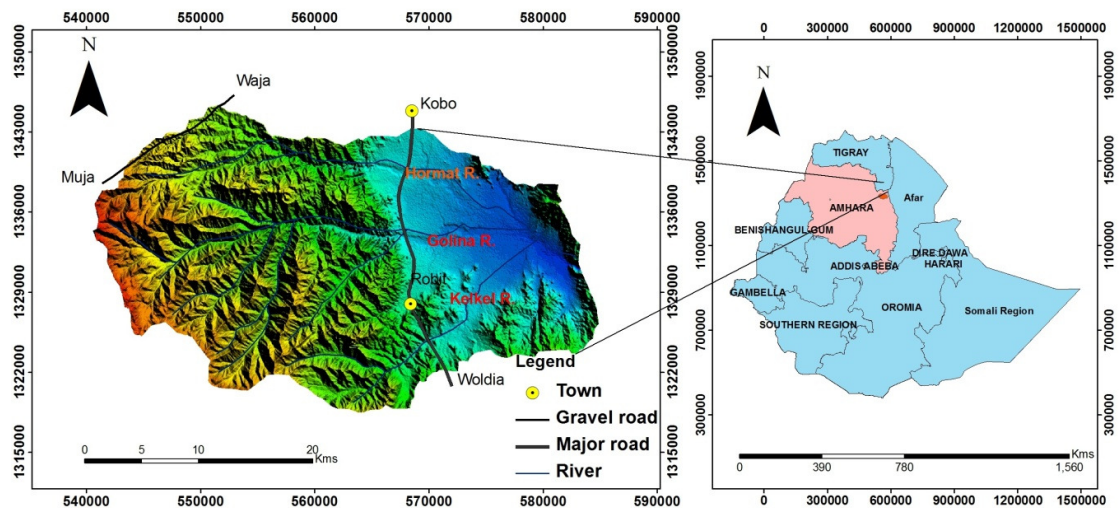


Figure 2.1: Location map of the study area

2.2. PHYSIOGRAPHY

The studied catchment has three types of physiographic features: the intermountain valley part, the valley escarpment, and the Mountainous area. There is a large topographic difference between the valley and the highland. The lowest elevation is the outlet of Golina stream (1304m.a.s.l) and the highest is Aboyi Gara mountain (3974 m a.s.l).The average altitude of the valley floor ranges from 1355 m a.m.s.l. to 1610 m a.m.s.l, while the mountain ridges range from 1610m a.s.l. to 3600 m a.s.l (Figure 2.2).

The valley is characterized by a graben-like structure bounded by north- south trending mountains in the west and east of the valley. The chain of mountains bordering the valley on the western part are marked by highly dissected steep slope deep gorges and canyons,

because of east-west and north-south trending faults that might be associated with marginal rift system.

Steep to vertically dipping escarpment faces bordering the plateau are common particularly on western margins. In some instances rock falls are common in this area.

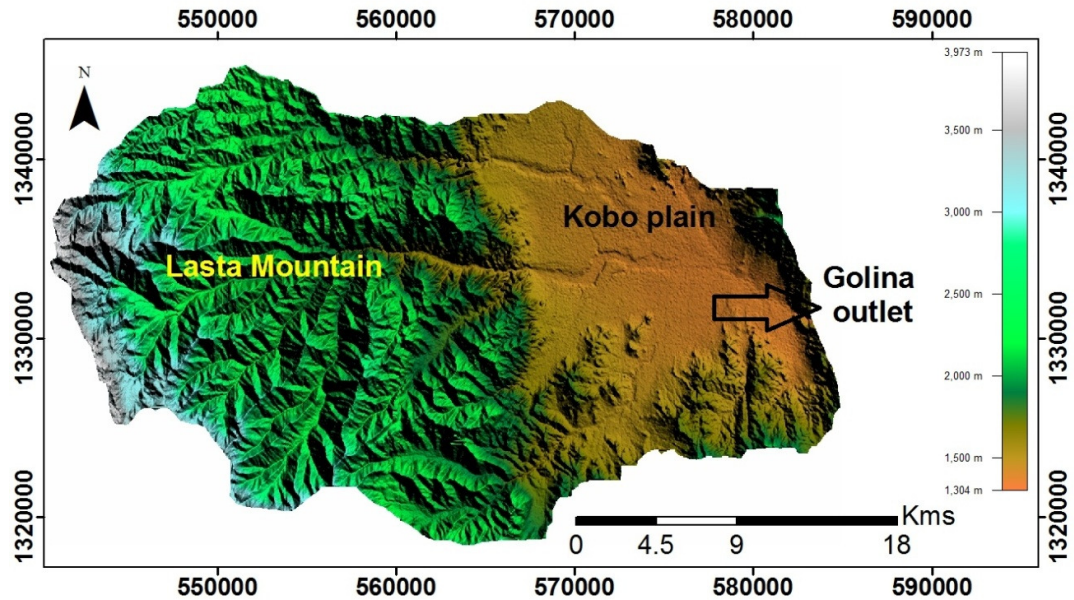


Figure 2.2: Digital Elevation Model showing Physiography of the area

2.3. DRAINAGE

Golina, Hormat, and Kelkel are some of the major rivers, which drain to the east (E) following the regional topography (Fig. 2.3). It is extensive drainage system arising from the mountain of the escarpment and shoulder areas of the southern and northern part of the study area. Intermittent rivers are dominant. The streams networks commonly show dendritic drainage pattern in the upstream areas and sub parallel pattern in the down course sections. They generally form high drainage density in the plateau and escarpment areas and low in the plain. In rainy season most of these Rivers are dumping most of its coarse sediments in the plain before reaching their outlet in the Zoble mountain chain. However in heavy rainy season leads its way to the Afar depression through Golina out let (Fig. 2.2).

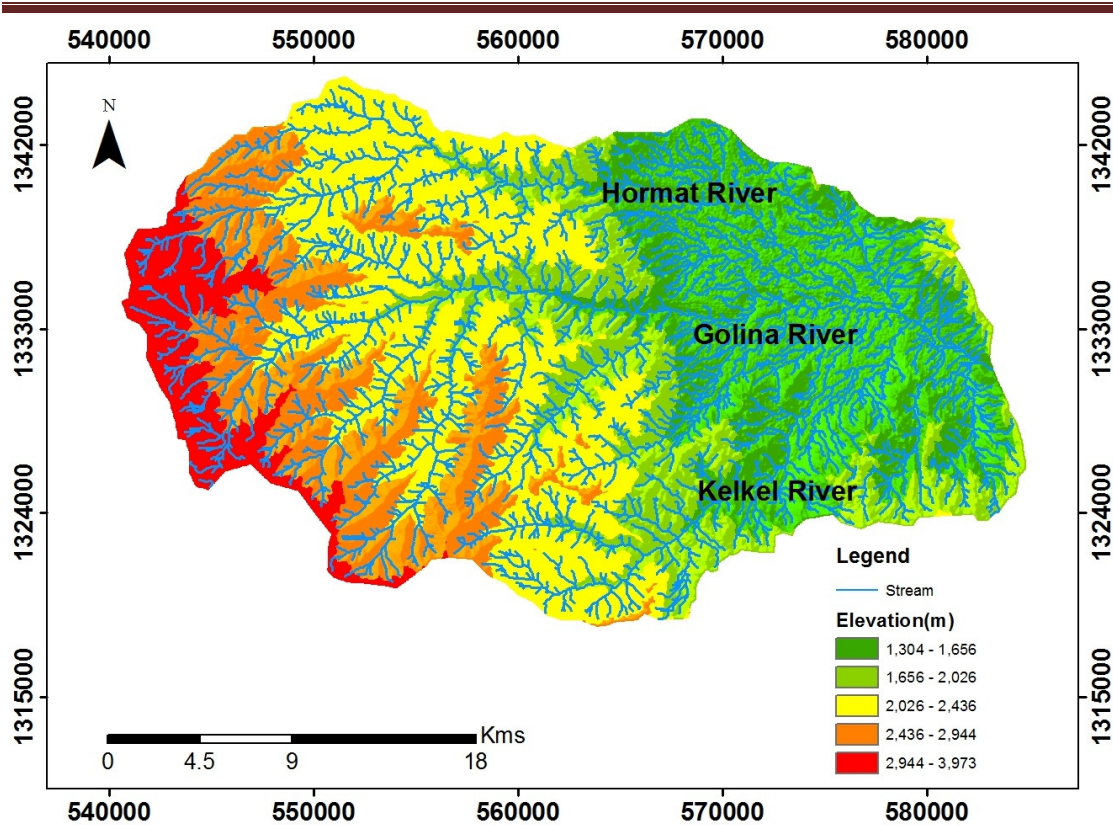


Figure 2.3: Simplified Topographic and drainage map of the study area

2.4. CLIMATE

The spatial and temporal variation of rainfall in Ethiopia is strongly controlled by the inter-annual movement of the position of the Inter Tropical Convergence Zone (ITCZ). During its movement to the north and south of the equator, the ITCZ passes over Ethiopia twice a year and this migration causes the onset and withdrawal of winds from north and south. When the ITCZ is located in the south, the Trade Winds from north drifts the equatorial winds. This periodical anomaly of winds causes seasonal rainfall variability. The big summer rains or *Kiremt rains* occur when the ITCZ is found north of Ethiopia (Daniel Gemechu, 1977). Climate of the study area ranges from semi-arid in the Kobo plain to humid in the mountains of the escarpment. The classification is made on the basis of the elevation above mean sea level of the areas. The principal feature of rainfall in the area is seasonal, poor distribution and variability from year to year. Rainfall distribution over the area is Bimodal, characterized by a short rainy season (Belg) and the long rainy season (Meher) that occurs in February-April and (kiremt) July-October respectively with a short dry spell (May to June) in between. The average monthly temperatures in Kobo area range from 19°C in December to about 26°C in June.

2.5. LAND USE/LAND COVER AND SOILS

2.5.1. LAND USE/LAND COVERS

Land use/land cover map of the area is used for the purpose of evapotranspiration estimation (chapter 4). It is prepared based on field observation and satellite imageries. Land cover units are incorporated in the soil – water balance model by way of rooting depth. In terms of areal coverage the important land cover units are agricultural land, shrub/bush land, forest, and River course cover a small area.

2.5.2. SOIL

Soil map of the study area was used to estimate soil water holding capacity in the course of actual evapotranspiration using soil – water balance approach. It shows the influence of soil parent material and the spatial variability in the degree of weathering. Soils are formed on account of the climate, physiographic, geology and other factors responsible for soil formation and development.

According to FAO textural soil classification (FAO 1997) and the Land use/land cover practice of the area, the soil of the basin is reclassified into three classes (fig 2.4).

Class – 1:- it covers the mountainous area about 72% of the total watershed area. It is dominated by Leptosols soil. It is sandy, silty clay and clay textural class soil with moderately to deep root Bushland and Grassland is dominant vegetation type. The weathering product of basaltic and pyroclastic deposits is the major source of this class of soil.

Class – 2:- This class is dominated by Vertisols soil type and clay texture. It has a well developed soil Profile and thick. It covers the valley part of the study area. The area classified under this class is extensively cultivated and moderately deep rooted crops such as corn and cereals are grown.

Class – 3:- texturally these soils are the same as class – 1 and the dominate soil type is Cambisols, but the degree of cultivation and vegetation practice differ. Moderately deep rooted crops such as corn and cereals are commonly grown. This class has covered the escarpment areas. Their topographic position and low coherence of matrix materials make these soils sensitive to erosion.

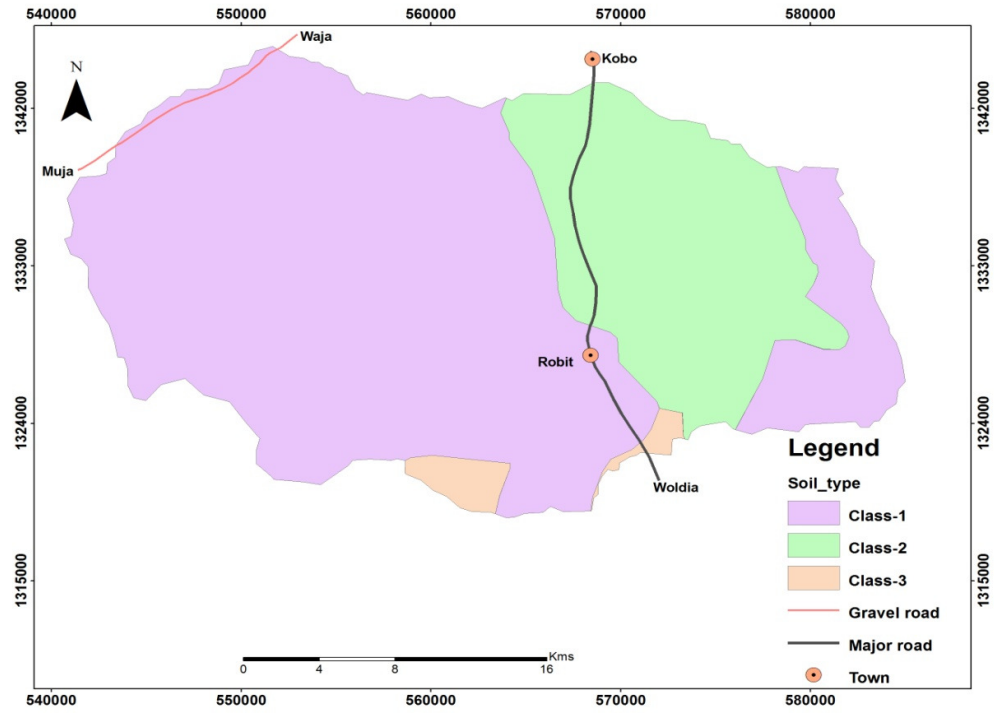


Figure 2.4: Reclassified FAO (1975), Soil map of the area

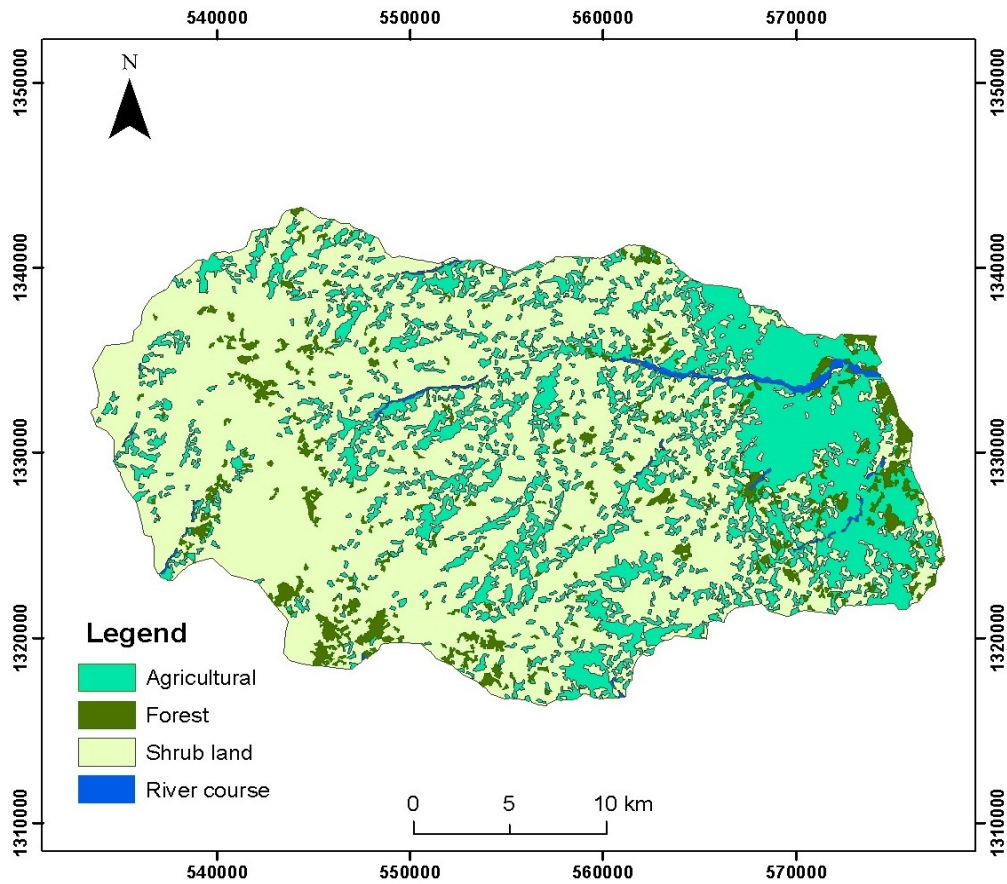


Figure 2.5 Classified land use/land cover of the area

CHAPTER THREE

3. GEOLOGICAL AND STRUCTURAL SETTING

3.1. REGIONAL GEOLOGY

3.1.1. FLOOD BASALTS OF ETHIOPIA

The continental flood basalts of Ethiopia are commonly termed as the Trap series to distinguish them from the post rift Aden series. Generally there are two views concerning the stratigraphy of this thick volcanic pile. The first one is classifying the flow into two distinct chronostratigraphic units: the Pre Oligocene stage: Ashange basalt; and the Oligocene – stage: Aiba basalt, Alaji fissural basalts and Rahyolites and Termaber basalts (Zenetin et.al, 1980, Berhe et.al, 1987). The second prevailing view is considering this volcanic pile as a continuous lava sequence from the base to the top of the plateau (Pik et.al, 1998)

Flood basalt eruption in Ethiopia has been reliably dated as being active from 43My to 9My ago, but particularly vigorous fissure eruptions occurred during the 32 – 21My interval. While localized fissure activity on the present plateaus has continued into Quaternary time, fissure basalt volcanism migrated into the Afar depression about 5My ago where it was most active between 4.5 and 1.5My. (Mohr and Zanettin, 1988)

The Cenozoic Ethiopian continental flood basalt province is located at the junction of three rifts: two oceanic rifts, the Red sea and Gulf of Aden, and the East African continental rift (Pik, et.al, 1998). This basaltic pile covers approximately 600,000 km² and a volume of 350,000 km³ (Mohr and Zanettin, 1988). Both plateau and shield building fissure eruptions have contributed to the building of the Ethiopian basalt pile. The period of most voluminous volcanism in Ethiopia was late Oligocene – early Miocene (32 – 21My), with flood emission of transitional basalt lava from the margins of the proto rift system extending for hundreds of kilometers over the present plateaus.

The Ethiopian flood basalt province appears unique in the frequency and volumetric importance of its intercalated silicic volcanics. Trachyte – rhyolite ignimbrites, both sub-alkaline and alkaline, can comprise up to 10%, rarely 25%, of the volume of the entire flood basalt pile at a given location. They are usually concentrated in the upper portion of the pile. (Mohr & Zenettin, 1988)

3.1.2. THE GEOLOGY OF NORTH-CENTRAL ETHIOPIA

The geology of north and central Ethiopia, of which the study area is part, is dominated by Tertiary volcanic strata underlain by Mesozoic sedimentary rocks. The volcanic rocks are predominantly fissural basaltic lava flows with silica varieties and central type volcanoes confined to the upper parts of the succession. The eruption occurred from Paleocene to Miocene separated by periods of quiescence and two groups are recognized in northern and central Ethiopia; the Ashangi and Megdala groups (CoESERAR, 1997).

The Ashangi Group is composed of compact commonly amygdaloidal basalts, sometimes porphyritic and often with olivine. The plagioclase is usually labradorite. Interbedding of basaltic pyroclastics is common. In the upper part, the Ashangi group becomes more tuffaceous and contains interbedded lacustrine deposits and some acid volcanic. The maximum thickness of the Ashangi Group recorded is 1200m, near Korem (CoESERAR, 1997).

The Megdala Group consists of fissural volcanics of basaltic and silicic composition at the bottom of succession, and central type and more silicic rocks at the top. As a whole the Megdala Group is composed predominantly of acidic rocks with interbedding of lavas and agglomerates of basaltic composition.

Petrochemically, alkalinity increases from the bottom of the Ashangi Group upwards. Thus, while rocks of the Ashangi Group are tholeiitic to transitional composition, for the Megdala Group, the fissural rocks are transitional and the central type ones are alkaline (CoESERAR, 1997).

Tectonic features of faulting and tilting constituted by numerous small normal step faults are particularly developed along the eastern margin of the Ethiopia Plateau to form the escarpment zones separating the Ethiopian Plateau from the Afar Depression. While the total displacement reaches 2000 to 2500m, maximum displacements are confined to the lower part of the escarpment zone where the faulting is mainly concentrated. According to Kazmin (1972) the escarpment zone in general can be taken as a two-step fault, the first of which is the down throw of 1000-2500m bounded at the foot-hills by the major faults and the second one, represented by blocks tilted towards Afar. Between the two steps occur a chain of marginal grabens following the major faults. These marginal grabens are narrow elongated depressions bounded on both sides by normal faults facing each other.

3.2. LOCAL GEOLOGY

The studied area is a basin at the western edge of the Danakil basin. The main lithological units in the study area are basaltic rocks that form the western highlands and escarpments, Acidic lava and pyroclastic flow deposits of rhyolitic compositions which form the eastern ridge (Zobel ridge) overlying the basalt and Quaternary to recent sediments mainly cover the study area (Fig 3.4).

3.2.1. THE BASALTIC ROCKS

Large parts of the study area, mostly the western and eastern mountainous terrains bounding the basin are covered by the highly weathered basalt and associated pyroclastics. According to CoESERAR (1997), the maximum thickness of this succession is about 1000 meters.

The basaltic rocks that form the western highlands and escarpments of the area are characterized by fine grained and light to dark greenish gray, light pinkish fine grained, and dark olivine, plagioclase, pyroxene and hornblende porphyry basalt layers. It is slight to moderately fractured and highly weathered in the upper part. Aphanitic basalt dykes intrude this formation at places. Owing to a number of fractures, faults and lineaments, it is possesses highly rugged topographic terrain.

The basaltic rock in the eastern highland show slight to moderately weathering and well fractured. It is overlain by slightly fractured and weathered Rhyolite.

3.2.2. ACIDIC LAVA AND PYROCLASTIC FLOW ASSOCIATIONS

This rock unit is extensively exposed in the adjoining escarpment forming Zoble and parts of Lasta Mountain and as isolated hills in the alluvial sediment of Kobo plain. The acidic lava flows (rhyolites) are exposed forming NE-SW oriented isolated hills within the graben fill and in adjoining escarpments intercalating with pyroclastic flows. This unit is often light pink with K-feldspar, plagioclase, quartz and some mafic minerals porphyry, and at places it is quartz, K-feldspar and plagioclase porphyry. Light pink, fine-grained rhyolite outcrop was seen with basalt xenoliths above the basalt, at the outlet of Golina stream to Afar (Sileshi Mamo, 2007).

These rocks are deformed and developed a generally NNE-SSW and ENE-WSW trending joints dipping to the E and SW, out of which the ENE-WSW trending appear younger and dominant ones (ORDA, 2008). Commonly, these rocks are intensively weathered and affected by non-systematic joints and it appears like basalt at places. According to ORDA these rocks are cut by sets of NNE-SSW basaltic dikes having thickness of >50cm at the

same time these dikes also affected by two sets of joints (E-W, NNE-SSW) and are thick to the escarpment areas. Along Kobo-Zoble road these are highly fractured as a result of the local faulting.

The pyroclastic flows mainly consist of lithic tuffs, volcanic agglomerate and are well-exposed in the down courses of the westerly draining streams of Zoble ridge intercalating with lava flows. These rock types frequently intercalate with each other and display variety of colors, but commonly show whitish, dark grey and reddish grey colors. These rocks contain lappili to cobble size rock fragments and are exposed alongside the Kobo-Zoble all weather road. It is often intensely weathered and is friable. Locally, outcrop scale sub-vertical joints affected these rocks.



Figure 3.1: Rhyolite that shows NNE-SSW and ENE-WSW trending set of joints (Pen is oriented to the East) adopted from ORDA, 2008.



Figure 3.2: NNE-SSW trending Aphanitic Basalt forming a dyke

3.2.3. QUATERNARY TO RECENT SEDIMENTS

all the plan area of the basin are covered by unconsolidated sedimentary deposit originated from adjoining elevated areas as a result of the denudation process acted up on them. The composition of this deposit consists of sediments of alluvial, coluvial and lacustrian origins (CoESERAR, 1997). According to CoESERAR the thickness of this sediment in Kobo basin from geological logs of existing boreholes and from geophysical investigations are varies from few tens meters in the west to over 350 meters in the eastern part of the plain.

The alluvial sediments are classified into fine to coarse grained according to the energy of the river and depositional basin width and depth. The most frequently observed ones are fine grained which are deposited along flat laying plains where the river looses energy at the curves. These sediments are unconsolidated and silty to sandy size, which show sub-horizontal deposition (bedding structure).The coarse grained ones are found by the side of high-energy riverbeds and contain pebble-cobble size rock fragments (Golina, Hormat and others). In general, as one goes from center of the plain towards the adjoining escarpments the grain size of the sediment increases.

At the foot of the valley and slope of escarpments (Lasta and Zoble), there are piles of colluvial deposits of rhyolitic and basaltic origin. This is taluse-like deposits resulted from gravitational force assisted by runoff and wind. The size of these deposits varies from gravel size to very large blocks of basalt with the basalt proportion dominant over the rhyolitic ones (ORDA, 2008).



Figure 3.3: Alluvial deposit along the stream cut

3.3. STRUCTURE

Kobo valley is found at the western most range of the down throw block in the vicinity of the great escarpment of the Ethiopian Rift Valley. Tensional movements along weak zones give rise to fissural volcanism followed by block faulting and tilting to form the escarpment zones including the marginal graben (CoESERAR, 1997).

Faults have often NW-SE strike and some have N-S and NE-SW trend. E-W and ENE-WSW running cross faults with minor displacement are also seen (Sileshi Mamo, 2007). However, the later tectonic events responsible for the occurrence of an east-west trending faults have also roles in determination and shaping of the existing land form and drainage characteristics (CoESERAR, 1997).

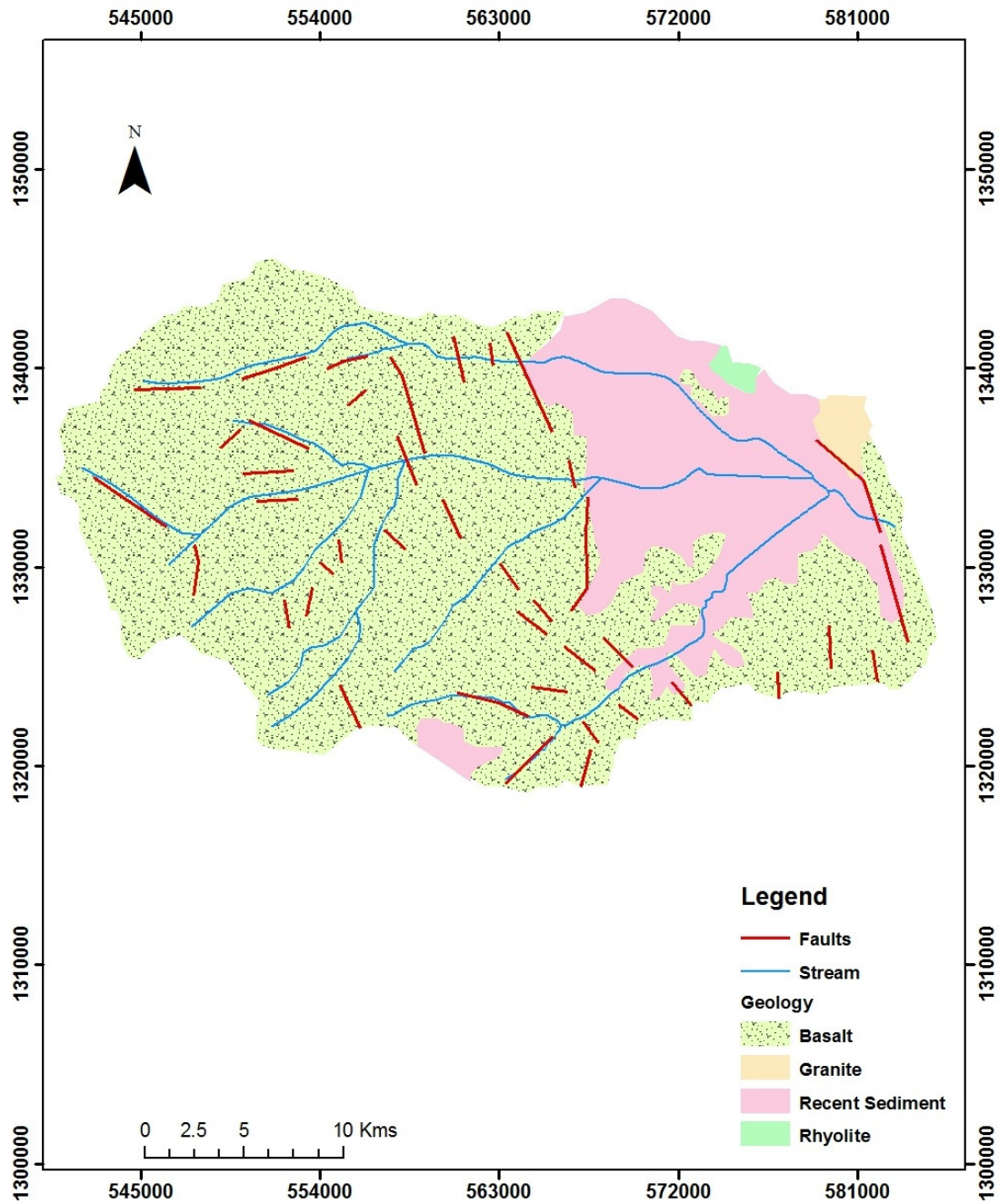


Figure 3.4: Geological map of the area (modified from Sileshi Mamo, 2007)

CHAPTER FOUR

4. HYDROMETEOROLOGY

4.1. GENERAL

Any water resource projects are influenced by the meteorological variables of the project area. The most useful hydrometeorological variations are precipitation, evaporation, evapotranspiration, solar radiation (sunshine hours), air temperature, relative humidity, soil moisture, stream discharge and water quality (Raghunth, 1987). The data were collected from stations within and nearby of the study area from National Meteorological Services Agency (NMSA), which altogether affect the hydrogeological and geological behavior of the terrain. Various climatological parameters of the study area have been summarized below.

Table 4.1 Location of meteorological stations used for different parameters

Station	Altitude M.a.s.l.	Location (UTM)	
		E	N
Alamata	1547	560502	1372456
Waja	1446	565315	1357995
Kobo	1524	568641	1343604
Korem	2466	556673	1382295
Maichew	2438	558432	1412871
Zoble	2139	581470	1354118
Muja	2749	531341	1326927
Sirinka	1861	566889	1299062
Woldia	2020	565351	1311025

4.2. TEMPERATURE

One of the factors affecting evaporation is temperature of the evaporating surface. The rate of evaporation is dependent on the temperature at the evaporating surface and that of the ambient air. The amount of water vapor in the atmosphere is directly related to the temperature (Shaw 1994). The temperature of the study area varies with altitude. The temperature data (Table 4.2) recorded show that the low land (Kobo, Waja, and Alamata) has higher temperatures recorded than the high land (Korem and Maichew). The highest mean maximum temperatures occur in the months of May to July (32.1°C to 34.3°C, 32.6 °C to 34.7 °C and 31.9 °C to 33.8 °C) and the lowest mean minimum value occur in the

month of November to January (11.0°C to 12.8°C, 9.7 °C to 12 °C and 11.7 °C to 12.7 °C) (1996-2005) in Kobo, waja, and Alamata stations respectively. Similarly, the Korem and Maichew station has the highest mean maximum temperatures in the months of April to June (23°C to 25.4°C and 22.8 °C to25.4 °C) and the lowest mean minimum values occur in the month of December to February (3.7°C to 5.8 °C and 6.7 °C to 8.1 °C) respectively.

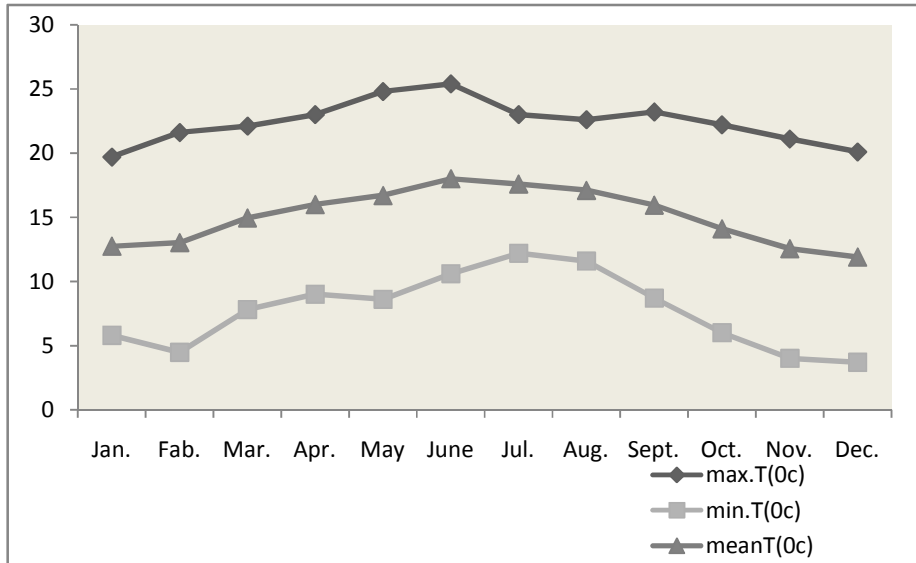


Figure 4.1: Mean monthly Temperature in (°C) at Kobo station (1996-2005).

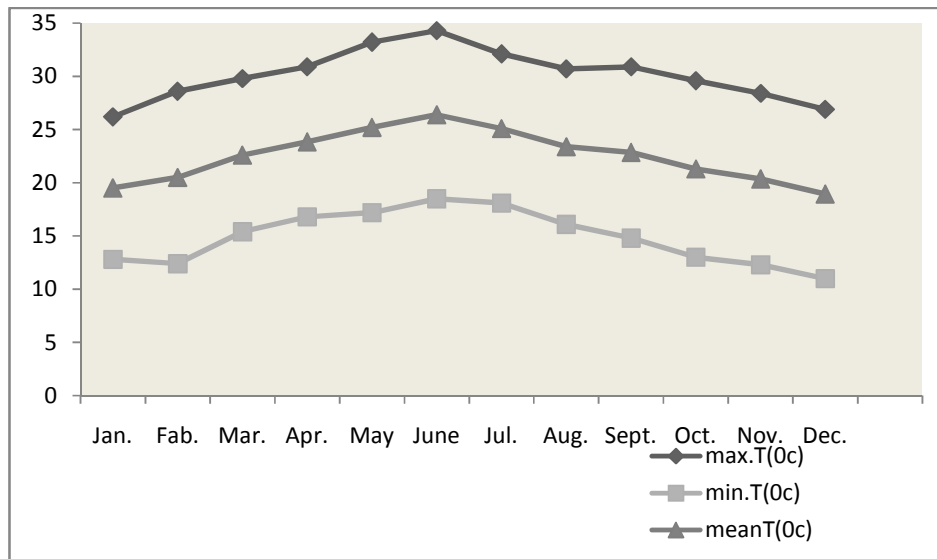


Figure 4.2: Mean monthly Temperature in (°C) at Maichew station (1996-2005).

Table 4.2: mean monthly minimum and maximum temperature

Station	Elevation		Mean monthly minimum, maximum and average air temperature (1996-2005)												Mean annual
			Jan.	Fab.	Mar.	Apr.	May	June	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	
Kobo	1524	max.T(°c)	26.2	28.6	29.8	30.9	33.2	34.3	32.1	30.7	30.9	29.6	28.4	26.9	30.1
		min.T(°c)	12.8	12.4	15.4	16.8	17.2	18.5	18.1	16.1	14.8	13.0	12.3	11.0	14.6
		meanT(°c)	19.5	20.5	22.6	23.9	25.2	26.4	25.1	23.4	22.9	21.3	20.4	19.0	22.4
Waja	1446	max.T(°c)	27.6	29.4	29.7	30.6	32.6	34.7	32.6	30.5	31.3	30	29	28.4	30.5
		min.T(°c)	12	11.9	14	14.7	15.7	16.8	17.6	17.1	15.5	13.1	11.3	9.7	14.1
		Mean T(°c)	19.8	20.7	21.9	22.7	24.2	25.8	25.1	23.8	23.4	21.6	20.2	19.1	22.3
Alamata	1547	max.T(°c)	27.0	28.9	30.0	30.8	32.8	33.8	31.9	30.3	30.6	30	28.8	27.7	30.2
		min.T(°c)	12.3	13.0	14.6	16.0	17.0	17.6	17.1	15.6	14.7	13.7	12.7	11.7	14.7
		Mean T(°c)	19.7	21.0	22.3	23.4	24.9	25.7	24.5	23.0	22.7	21.9	20.8	19.7	22.5
Korem	2466	max.T(°c)	19.7	21.6	22.1	23.0	24.8	25.4	23.0	22.6	23.2	22.2	21.1	20.1	22.4
		min.T(°c)	5.8	4.47	7.81	9.0	8.6	10.6	12.2	11.6	8.7	6.0	4.01	3.7	7.7
		Mean T(°c)	12.8	13.0	15.0	16.0	16.7	18.0	17.6	17.1	16.0	14.1	12.6	11.9	15.1
Maichew	2438	max.T(°c)	19.6	21.2	22.1	22.8	24.3	25.4	22.7	22.2	22.6	21.1	20.3	19.4	22.0
		min.T(°c)	7.7	8.1	10.1	11.2	11.9	13.6	13.1	12.7	10.7	8.6	7.3	6.7	10.1
		Mean T(°c)	13.7	14.7	16.1	17.0	18.1	19.5	17.9	17.5	16.7	14.9	13.8	13.1	16.1

Table 4.3: Mean monthly wind speed (m/s)

		Mean Monthly Wind Speed (U) 2m above ground level (m/s) (1996-2005)											
Station	Jan.	Fab.	Mar.	Apr.	May	June	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Mean annual
Kobo	1.8	1.9	2	1.9	1.7	2	1.9	1.6	1	1	1.1	1.2	1.6
Maichew	1.1	1.3	1.3	1.3	1.4	2.2	3.3	2.5	1.2	1.1	1.1	1.1	1.6

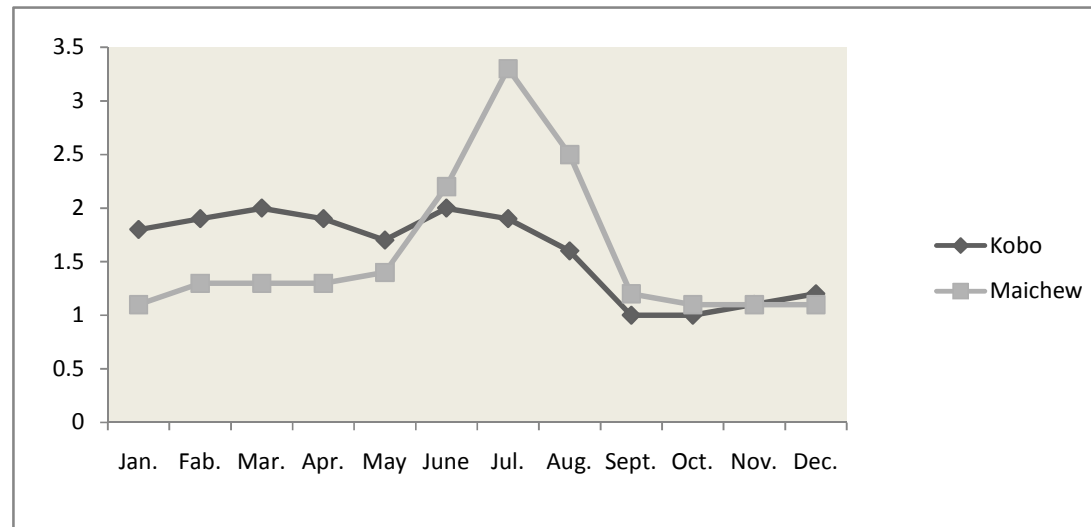


Figure 4.3: Mean monthly wind speed (m/s) (1996-2005)

Table 4.4: mean monthly sunshine hours

Station	Mean Monthly Sunshine Hours (hour/day)												
	Jan.	Feb.	Mar.	Apr.	May	June	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Mean annual
Kobo	7.8	7.4	8.4	8.2	8.6	6.6	5.3	6	6.7	8.5	9.3	8.5	7.6
Maichew	7.1	8.1	7.2	8.2	8.8	7.0	5.0	5.4	6.9	7.6	7.8	7.8	7.2

4.3. WIND SPEED

Presence of atmospheric turbulence can greatly increase the rate of evaporation by removing vapor from evaporating surface and giving space for fresh air capable of holding additional vapor in the atmosphere. The replacement of saturated air by drier air would enable evaporation to continue.

At Kobo and Maichew stations, a ten year record of wind speed at an elevation of 2 meters above ground surface has been considered. The mean monthly wind speed of the area varies from 1 ms^{-1} in September to 2.04 ms^{-1} in March with average value of 1.6 ms^{-1} at Kobo. For Maichew station, it varies between 1.1 ms^{-1} in January and 3.3 ms^{-1} in July and the average value of 1.6 ms^{-1} (Figure 4.3 and table 4.3).

4.4. SUNSHINE HOURS

Since the evaporation requires continuous supply of energy, which is derived mainly from solar radiation will be a factor of considerable importance.

Sunshine hour duration data are available for Kobo and Maichew stations. Mean sunshine hours determined for the Kobo station was above 8.0 hours in the months of October to December and March to May. In the other months, it decreases up to 5.3. The highest cloud cover occurs from July to September. A lesser cloud cover or sunny skies exist in all other months. The mean monthly sunshine durations at Kobo and Maichew stations were 7.6 and 7.2 hours respectively.

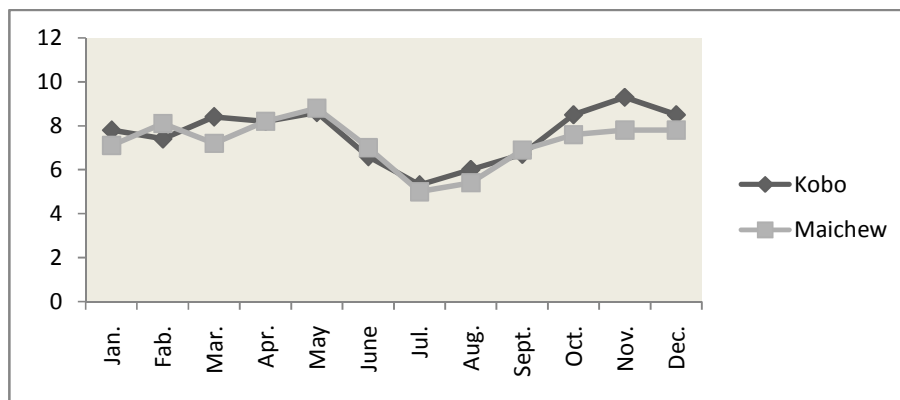


Figure 4.4: Mean monthly sunshine hour (1996-2004).

4.5. RELATIVE HUMIDITY

Relative humidity is the percentage of moisture in air relative to the amount it can hold at saturation at a given pressure and temperature. The relative humidity of the air is largely dependent on temperature and temperature. Data on relative humidity is available from two

stations at Kobo and Maichew. The mean monthly relative humidity for kobo ranges from 38% in June and 67% in January. For Maichew it ranges from 43% to 68%.

Table 4.5: Mean monthly relative humidity (%) (1996-2004).

Station	Jan.	Feb.	Mar	Apr.	May	June	Jul.	Aug.	Sept	Oct.	Nov	Dec.	Mean annual
Kobo	66.5	55.0	50.7	53.6	48.6	37.8	52.1	62.7	62.0	53.0	49.5	58.2	54.8
Maichew	67.5	53.5	60.9	56.7	47.9	43.1	61.2	66.5	60.9	63.2	60.7	61.6	58.6

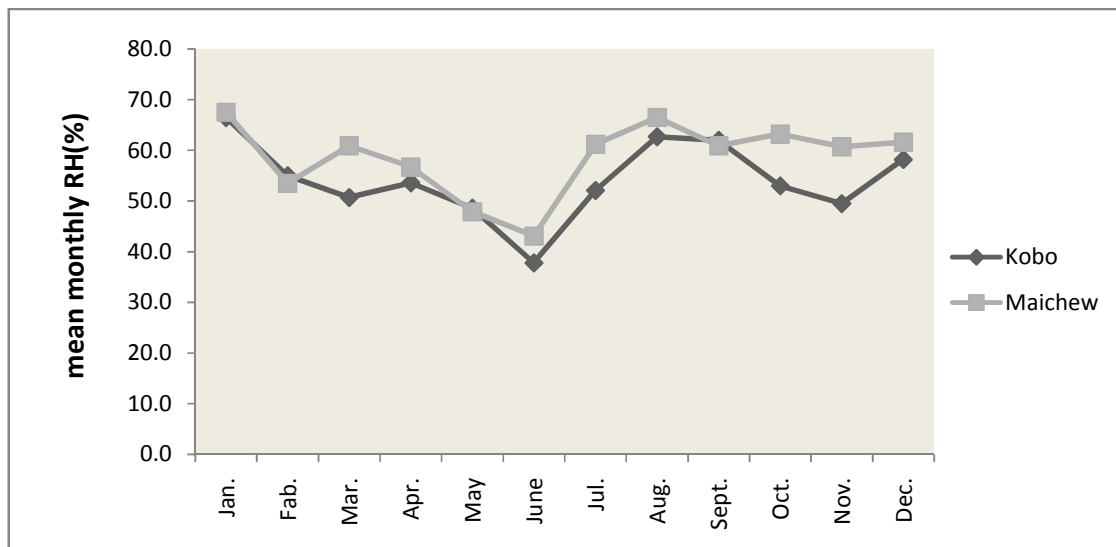


Figure 4.5: Mean monthly relative humidity (%)

4.6. PRECIPITATION

The inter-annual oscillation of the surface position of the Inter-Tropical Convergence Zone (ITCZ) causes variation in the wind flow pattern over Ethiopia. In its oscillation to the north and south of the equator, the ITCZ passes over Ethiopia twice a year and this migration alternately causes the on-set and withdrawal of winds from north and south. Due to this phenomenon, the valley and highland part of the study area receive Bi-modal type of rainfall pattern (figure 4.7 and 4.8). The main rainy season known as “Kiremt” occurs from June to September when the ITCZ is in north. During this period, the south west equatorial westerlies from the Atlantic Ocean cause high rainfall over Ethiopia. For the project area the on-set of “Kiremt” rain is in July. The smaller rainy season called “Belg” rain occurs in March, April and May when the ITCZ lies across southern Ethiopia. During this period, the most easterly and southeasterly winds from Indian Ocean produce the “Belg” rain to the east central and north western highlands and associated lowlands including the study area valley. The mean on-set of the Belg rain is in March.

Rainfall data with a period of record from 8 to 16 years are available from 7 stations. Out of these stations, Kobo station is located within the study area. Most of these stations are aligned linearly in north-south direction, whereas the eastern and western highland parts of the basin have no stations. Korem and Maichew were the only gauging stations in the western highlands that nearly close to the studied catchment. Thus, the low density, uneven distribution with large number of missed data may not be adequate for a thorough assessment of the spatial and temporal variation of rainfall.

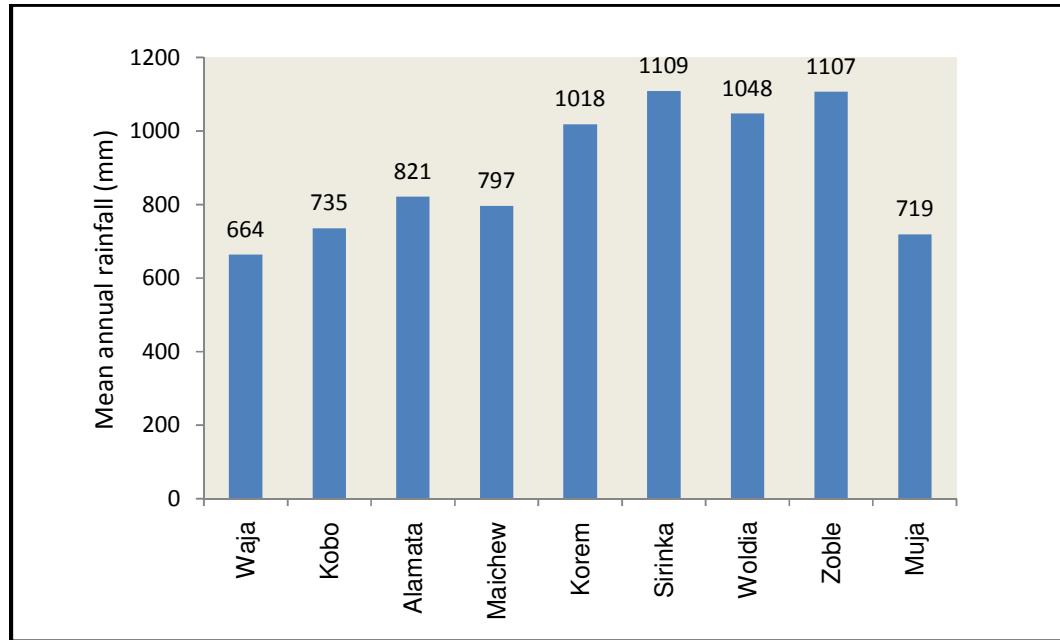


Figure 4.6: Mean annual rainfall (mm) of the station within and around the study area

There are many physical factors controlling the depth and distribution of precipitation in a given catchment. Surface elevation is one of the powerful factors affecting the depth of precipitation in a given area which positively affects the depth of precipitation. However, in this river catchment instead of surface elevation (Correlation coefficient between rainfall and altitude is 0.101 i.e. poorly correlated) the rainfall is greatly affected by local rain shadow, the position to rain bearing winds (with lee and windward orientation), and Orographic effect.

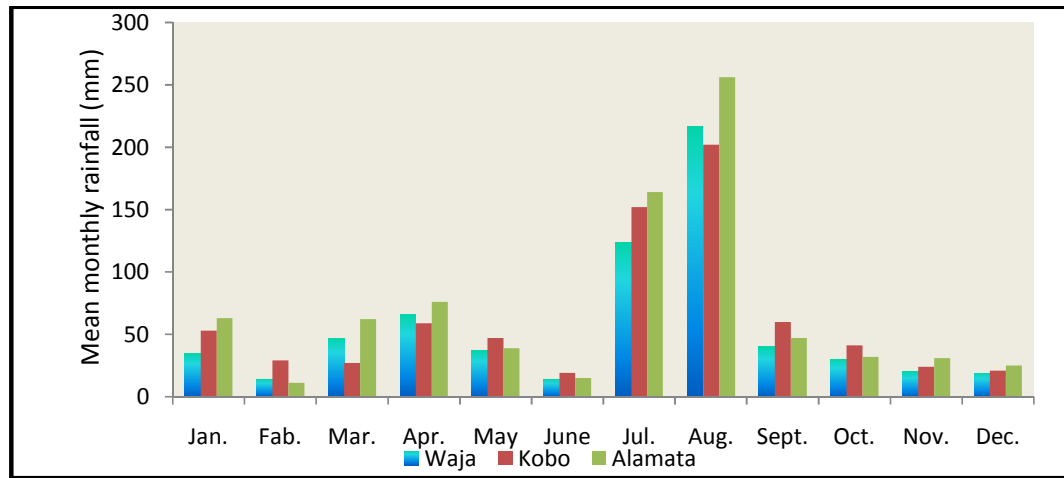


Figure 4.7: Mean monthly precipitation trend of floor of Raya- kobo valley (1995-2005) (Bi-modal rainfall pattern zone)

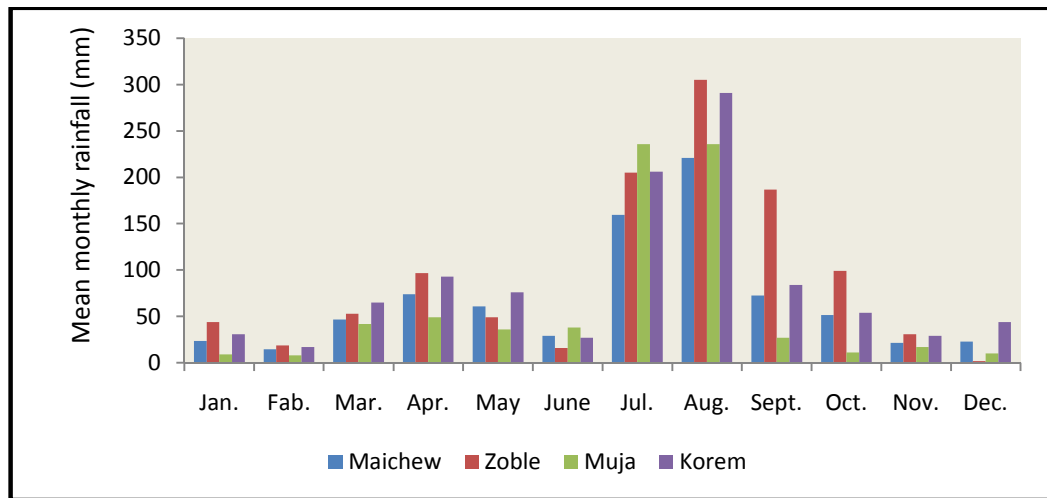


Figure 4.8: Mean monthly precipitation trend of western and eastern highland

4.6.1. ANNUAL AREAL DEPTH OF PRECIPITATION

The rainfall measurement is a point observation and may not be used as a representative value for the area under investigation. Therefore, the point measurements have to be averaged over the study area. To average the point measurements for the study area, three methods have been applied; Arithmetic mean, Thiessen Polygons, and Isohyetal Contour Map methods. All these used for comparison of one from the other according to the Orographic effect and areal distribution of the stations.

- A. **Arithmetic Mean** – is the simplest method of determining areal average rainfall. It involves averaging the rainfall depths recorded at a number of gages. This method is satisfactory if the gages are uniformly distributed over the area and the individual gage measurements do not vary greatly about the mean (Chow1988).

$P_A = \frac{\sum_{i=1}^n P_i}{n}$ where P_A is average rainfall for the total area, P_i is measured precipitation at a given station and time and n is number of rain gages.

Since, the three stations (Kobo, Waja and Alamata) are closely and evenly spaced on the floor of Raya- Kobo valley, arithmetic mean method was applied to determine the aerial depth of precipitation for the valley part of the study area.

The Arithmetic mean computed using these three gauges gives a value of **739mm** of rainfall (table 4.6).

Table 4.6: Mean annual areal depth of ppt. obtained from arithmetic mean of three different rainfall stations in and around the study area.

Station	Jan.	Feb.	Mar.	Apr.	May	June	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Waja	35	14	47	66	37	14	124	217	40	30	20	19	663
Kobo	53	29	27	59	47	19	152	202	60	41	24	21	734
Alamata	63	11	62	76	39	15	164	256	47	32	31	25	821
Mean	50	18	45	67	41	16	147	225	49	34	25	22	739

B. Thiessen method – assumes that at any point in the watershed the rainfall is the same as that at the nearest gage so the depth recorded at a given gage applied out a distance halfway to the next station in any direction. The relative weights for each gage are determined from the corresponding area of application in a Thiessen polygon network (Chow1988).

$P_A = \frac{\sum_{i=1}^n P_i a_i}{A_i}$ where P_i is observed precipitation, a_i is area where the station found, and A_i is the total area under investigation.

The Thiessen method is generally more accurate than the arithmetic mean method, but it is inflexible, because a new Thiessen network must be constructed each time there is a change in the gage network, such as when data is missing from one of the gages. Also, the Thiesson method does not directly account for orographic influences on rainfall. Thiesson polygon method was applied to see the mean annual rainfall for the entire study area. The weighted mean of the precipitation was calculating using the above equation which resulted in **929mm** of mean annual rainfall for the entire study area. The table used to compute the average rainfall depth using Thiesson polygon is given in table 4.7.

No.	Station	Area of influence (a _i) (km ²)	Catchment area(A) (Km ²)	Weighted area (a _i /A)	Annual ppt.(p _i)	(a _i /A)*(p _i)
1	Kobo	492.6	805.8	0.61132	735	449.319
2	Muja	128.9	805.8	0.15997	719	239.695
3	Woldia	184.3	805.8	0.22872	1048	239.695
Total		805.8	805.8	1	2502	929

Table 4.7: Annual weighted rainfall depth using Thiessen polygon

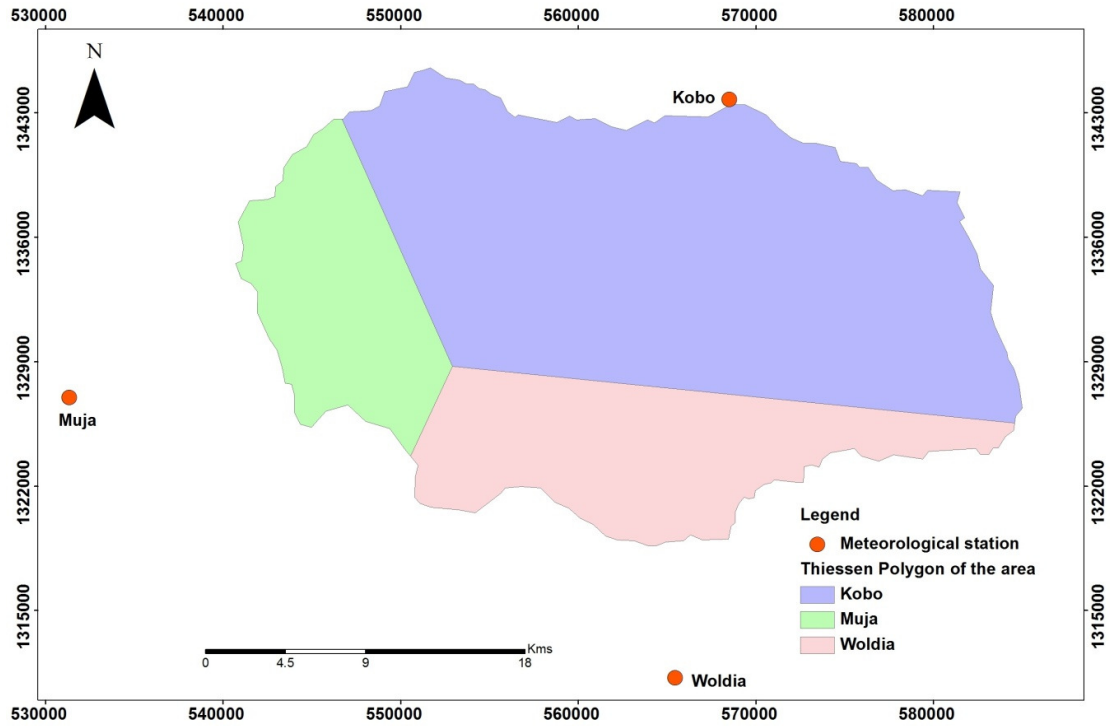


Figure 4.9: Thiessen polygon of the study area

C. **Isohyetal method** – overcomes some of these difficulties by constructing isohyets, using observed depths at rain gages and interpolation between adjacent gages. Where there is a dense network of rain gages, isohyetal maps can be constructed using computer programs for automated counterling (Chow1988).

$$P_A = \frac{P_{1,2} \cdot a_{1,2} + \dots + P_{n-1,n} \cdot a_{n-1,n}}{A_i}$$

Where P_{1,2} is rainfall between isohyets 1 and 2, a_{1,2} is area enclosed by successive isohyets of 1 and 2.

The isohyetal method is flexible, and knowledge of the storm pattern can influence the drawing of the isohyets, but a fairly dense network of gages is needed to correctly construct the isohyetal map from a complex storm.

Based on the above formula, mean annual precipitation of the study area has been obtained **871.53mm**. The table used to compute the average rainfall depth using isohyetal method is given in table 4.8.

No.	B/n contours (mm)	ppt. avg.	a_i	A	a_i/A	P_i	$(a_i/A)*P_i$
1	735-750	742.5	12	806	0.015	742.5	11.05
2	750-780	765	37	806	0.046	765	35.12
3	780-810	795	106	806	0.132	795	104.55
4	810-840	825	216	806	0.268	825	221.09
5	840-870	855	124	806	0.154	855	131.54
6	870-900	985	119	806	0.148	985	145.43
7	900-930	915	107	806	0.133	915	121.47
8	930-960	945	50	806	0.062	945	58.62
9	960-990	975	25	806	0.031	975	30.24
10	990-1010	1000	10	806	0.012	1000	12.41
Total							871.53

Table 4.8: Annual weighted rainfall depth using Isohytal method

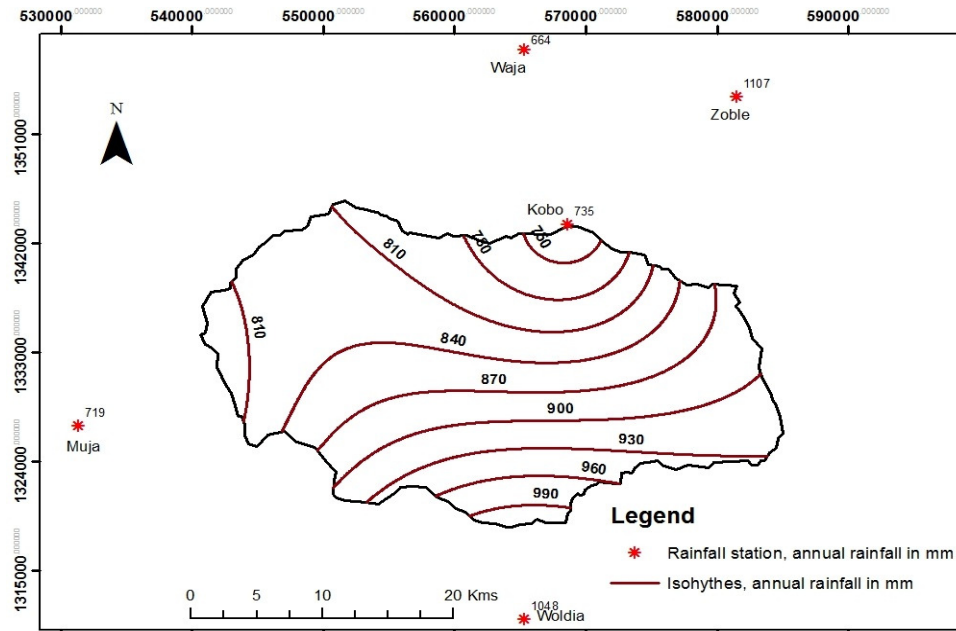


Figure 4.10: Isohyetal map of the study area

4.7. POTENTIAL EVAPOTRANSPIRATION (PET)

Potential evapotranspiration is the water loss if at no time there is a deficit of water in the soil for the use of vegetation (Thornthwaite, 1944). PE is dependent on the evaporative capacity of the atmosphere and can be calculated theoretically using meteorological data. The most commonly used methods for calculating PE are those of Blaney and Criddle (1962) and Thornthwaite (1948), which are based on empirical correlations between evapotranspiration and climatic factors, and Penman (1948) and Penman–Monteith

(Monteith 1965, 1985) which are energy-budget approaches requiring further meteorological data (Kevin, 2005).

The study area has variable climatic conditions due to different character of climatic elements such as rainfall, temperature, wind speed, relative humidity, and sunshine hours. Thus the catchment basin is sub-divided independently in to two: the highland and the rift floor sub-catchments. For each sub-catchment evapotranspiration is estimated one independent of the other.

Penman combination approach, Hargreaves and Thornthwaite approach are used in this study based on the available input data.

4.7.1. THORNTHWAITE METHOD

Thornthwaite method is based up on the assumption that potential evapotranspiration is dependent only on meteorological conditions and ignores the effect of vegetation density and maturity. The only necessary factors to calculate PET using these methods are mean monthly air temperature (T), Latitude and month (average monthly sun light) (Thornthwaite and Mather 1955 and 1957).

Given the monthly mean temperatures from the measurements at a climatological station, an estimate of the potential evaporation for each month of the year can be calculated (Shaw, 1994). The method has been used widely throughout the world, but strictly it is not valid for climates other than those similar to that of the area where it was developed, the eastern USA. Compared with the estimates from the Penman formula, Thornthwaite values tend to exaggerate the potential evaporation (Shaw, 1994). Contrary to this, in this case it underestimates the PET value of the area.

An estimate of the potential evapotranspiration, PET, calculated on a monthly basis, is given by:

$$PET_m = 16N_m \left(\frac{10T_m}{I} \right)^a \text{ mm}$$

Where: m is the months 1, 2, 3...12,

N_m is the monthly adjustment factor related to hours of daylight,

T_m is the monthly mean temperature °C,

I is the heat index for the year, given by:

$$i_m = [Tm/5]^{1.5}$$

$$I = \sum i_m = \sum \left(\frac{Tm}{5} \right)^{1.5} \text{ for } m = 1 \dots 12 \text{ and,}$$

$$a = 6.7 \times 10^{-7} I^3 - 7.7 \times 10^{-5} I^2 + 1.8 \times 10^{-2} I + 0.49 \text{ (to 2 significant figures)}$$

The Thornthwaite formula above gives PET for standardized month of 30 days and 12 hours of sunlight. While the daylight factors (N_m) are obtained by dividing the possible sunshine hours for the appropriate latitude by 12, this is taken from book of Shaw, 1994. The latitude of the study area is $11^{\circ}55'40''$ to $12^{\circ}10'11''$, which is very near to $10^{\circ}N$; thus the adjustment factor is taken based on $10^{\circ}N$.

Thus, the PET values obtained by Thornthwaite method for the rift floor (Alamata, Waja, and Kobo) and the highland (Korem and Maichew) are estimated to be 1098.8mm and 729mm respectively (see appendix 7).

4.7.2. MODIFIED PENMAN METHOD

The most general and widely used equation for calculating PET is the Penman equation. The Penman monteith variation is recommended by FAO. The FAO Penman-Monteith equation requires air temperature, humidity, radiation and wind speed data.

The basic equation of Penman to calculate potential evapotranspiration, PET_m is:-

$$PET^m = \frac{(\Delta/\square)HT + Eat}{\left(\frac{\Delta}{\square}\right)=1}$$

The procedure followed during calculation for the data presented in (table4.10) are given bellow. Estimation of annual PET by the Penman method for valley plain and the highland part of the study area are 1596.1mm and 1259.5mm respectively.

4.7.3. HARGREAVES METHOD

Hargreaves and Samani (1982, 1985) proposed several improvements to the Hargreaves (1975) equation for estimating grass-related reference ET (mm/ d); one of them has the form:

$$PET = aR_a T_d^{1/2} (T_a + 17.8)$$

Where; $a = 0.0023$ is a parameter;

T_d = the difference between maximum and minimum daily temperature in $^{\circ}C$;

R_a = the extraterrestrial radiation expressed in equivalent evaporation units. For a given latitude and day R_a is obtained from table. The only variable for a given location and time period is the daily mean, max, and min air temperature. Therefore, the Hargreaves method has become a temperature-based method. See appendix 3 for detail calculation.

For the same area the Thornthwaite formula underestimates by 31%, while Hargreaves method overestimates by 15% as compare to Penman (table 4.9).

Table 4.9: Annual PET (mmy-1) computed from different methods.

		Penman	Thornthwaite	Hargreaves
PET (mm)	valley floor	1596.1	1098.8	1887.5
	Highland	1259.5	729.0	1418.6

Generally, Penman Combination method is more appropriate than Thornthwaite and Hargreaves method as a result of using more meteorological parameters. So, the value obtained by Penman Combination method (1596.1mm and 1259.5mm) taken as the annual PET of the valley floor and highland part of the study area.

4.8. ACTUAL EVAPOTRANSPIRATION (AET)

Actual evapotranspiration (AET) is the quantity of water that is actually removed from a surface due to the processes of evaporation and transpiration. It is therefore, the amount of evaporation that occurs under a given climate and soil moisture and is less than or equal to potential evapotranspiration.

The most popular method of computing actual evapotranspiration is through calculation of potential evapotranspiration. When moisture conditions are suitable, the actual rate of evapotranspiration is equal to the potential rate. The methods by which AET are calculated:

4.8.1. EMPIRICAL FORMULA

4.8.1.1. TURC METHOD

A widely used formula to estimate annual values of AET for catchment areas and it representing all the different climates including Africa (Shaw, 1994).The formula takes into consideration mean annual precipitation and mean annual temperature of the catchment area.

$$AET = \frac{P}{\sqrt{0.9 + \left(\frac{P}{L}\right)^2}} \text{ mm per year}$$

Where P is the mean annual precipitation (mm), $L=300+25T+0.05T^3$ (mm) and T is the mean air temperature (°C).

Turc showed that the formula could be applied in humid and arid climates, either hot or cold (Shaw, 1994).

AET of each of sub-catchments estimated separately by taking averaging of mean annual precipitation of Korem and maichew stations for the highland and Kobo, Waja, and Alamata for the valley. Thus, AET values obtained by Turc method for highland and valley are 646mm and 684mm, respectively.

The AET value of the whole catchment estimated by this method could be obtained by averaging the AET values of the two sub-catchments together is 655mm.

4.8.2. SOIL WATER BALANCE METHOD

Water loss from a catchment area doesn't always proceed at the potential rate, since this is dependent on a continuous water supply. When the vegetation is unable to abstract water from the soil, then the actual evaporation becomes less than potential. On the other hand when there is abundant moisture in the soil, the actual evapotranspiration rate is equal to potential evapotranspiration.

After rainfall ceases, saturated soil loss water becomes unsaturated until it can just hold a certain amount against the force of gravity; it is then said to be at 'field capacity'. If there is no rain to replenish the water demand of the soil, the soil moisture become depleted by the demands of the vegetation to produce a soil moisture deficit (SMD), viz the amount of water required to restore the soil to field capacity.

The values of soil moisture deficit and actual evapotranspiration vary with soil texture and vegetation and Penman (1950) introduced the concept of a 'root constant' (RC) that defines the amount of soil moisture (mm) that can be extracted from a soil without difficulty by give vegetation (Shaw 1994). Therefore, the soil moisture budget can be made on a monthly basis for various type of vegetation classified according to their root constants.

Based on this Land use Land cover classification discussed in Section 2.5.1 and reclassified FAO (1975) soil classification Section 2.5.2 the estimated precipitation and potential evapotranspiration of the area, the actual evapotranspiration has been calculated using Thornthwaite and Mather standard soil water balance model.

In the model all the units are described in mm and the explanation to the symbols are listed below and the calculation is present in Appendix 9 for each land cover.

P monthly mean precipitation in mm,

PET estimated potential evapotranspiration of the area.

P-PET difference between rainfall and potential evapotranspiration, positive values indicate wet season and negative values indicate dry season. Positive values are representing additions of moisture to the soil while the negative values are showing the monthly demand of moisture by the vegetation which is not satisfied by the monthly rainfall.

APWL Accumulated potential water loss. Which indicates the severity of water shortage, is obtained by cumulating of the negative values of the differences between monthly

precipitation and potential evapotranspiration for dry season only; and the summation begins with the first month of dry season.

Sm soil moisture.

During dray month soil moisture can be calculated using the following formula.

$$S_m = W \exp\left[-\frac{(Lam)}{W}\right]$$

Where, Lam accumulated water loss at the month m, and W available water capacity of the root zone,

While during wet season Soil moisture values for each wet month are obtained by adding the excess of rain of the current month to the soil moisture of the month before. However, this sum may not exceed the water capacity and excess is booked as moisture surplus.

AET actual evapotranspiration of the month. To quantify AET of the month there are two cases; if $P_m > PET_m$, then $PET = AET$ and if $P_m \leq PET_m$, then $AET_m = P_m + S_{m-1} - S_m$, where

S_{m-1} and S_m are soil moisture during the month m-1 and m respectively.

SMD Soil moisture deficit ($PET_m - AET_m$)

S Soil moisture surplus.

TARO total available for runoff

RO River discharged

D Detention.

Parameter	Description
H_T	<p>The available Heat, calculated from incoming (R_I) & outgoing (R_o) radiation determined from sunshine records, temperature and humidity using the formula:-</p> $H_T = R_I(1 - r) - R_o; \quad R_I(1 - r) = 0.75R_a f_a \left(\frac{n}{N} \right)$ <p>R_a – Solar radiation (fixed by latitude and season and is constant for a given latitude and season, obtained from standard meteorological tables);</p> <p>- r the reflective coefficient for incident radiation or albedo of the vegetation covers of the catchment that depends on the nature of the surface.</p> <p>- $f_a \left(\frac{n}{N} \right)$ takes several forms based on latitude and for the study area latitudes south of $54 \frac{1}{2} ^\circ N$ is taken as $f_a \left(\frac{n}{N} \right) = \left(0.16 + 0.62 \frac{n}{N} \right)$ (Shaw, 1988) n- monthly mean sunshine hrs (from Meteorological record); N – Daylight factor (Fixed by latitude and season and is constant for a given latitude and season)</p> <p>- $R_o = \sigma T^4 (0.47 - 0.075\sqrt{e_d})(0.17 + 0.83n/N)$; σT^4 – the theoretical blackbody radiation at the temperature of the air (T in Kelvin scale);</p> <p>σ (Stefan –Boltzmann constant) = $5.67 \times 10^{-8} \text{ Wm}^{-2}\text{k}^{-4}$, e_d – the saturated mean vapor pressure at dew point(mm of mercury), $e_d = e_a (RH/100)$</p> <p>e_a – the saturated vapor pressure at air temperature(T_a), RH– Relative Humidity in % - obtained from meteorological record</p>
E_{at}	<p>The Energy for evaporation based on the air humidity and air temperature, the subscript t signifies inclusion of transpiration effects.</p> $E_{at} = 0.35 \left(1 + \frac{u_2}{100} \right) (e_a - e_d);$ <p>$e_a - e_d$ is saturation deficit, U_2 – Mean wind speed (miles/day) at 2m above the surface (from Meteorological record)</p>
Δ	<p>The slope of the curve of saturated vapor pressure against temperature corresponding to the air temperature (e_a at T_a against T_a). $\Delta = (e_a - e_d)/(T_a - T_d)$</p>
γ	<p>The reflective coefficient for incident radiations or the Albedo of the basin that depends on the nature of the surface.</p>

Potential Evapotranspiration calculated using Penman Combination method (Kobo)																			
Month	Parameters																		
	Tem _p (°C)	Tem _p (°K)	e _a (mm/d)	RH (%)	e _a (mm/d)	U ₂ (mile/d)	Sunshine hrs(n) (hr/d)	N (hr/d)	n/N	R _a (mm/d)	F _a (n/N)	R _f (1-r) (mm/d)	ET ⁴ (mm/d)	R _o (mm/d)	H _T	E _{at} (mm/d)	Δ/□	PET (mm/d)	PET (mm/month)
January	19.5	292.7	16.99	66.5	11.31	96.64	7.8	11.6	0.67	12.8	0.58	5.54	14.301	2.26806	3.27	3.9141	2.16	3.5	107.7
Febura.	20.5	293.7	18.08	55.0	9.94	102	7.4	11.8	0.63	13.9	0.55	5.72	14.498	2.33762	3.38	5.7514	2.32	4.1	114.7
March	22.6	295.8	20.55	50.7	10.41	107.37	8.4	12	0.70	14.8	0.59	6.59	14.917	2.55381	4.04	7.3598	2.35	5.0	156.0
April	23.9	297.1	22.23	53.6	11.91	102	8.2	12.3	0.67	15.2	0.57	6.54	15.181	2.31887	4.22	7.2988	2.42	5.1	153.5
May	25.2	298.4	24.03	48.6	11.69	91.27	8.6	12.6	0.68	15	0.58	6.56	15.448	2.43036	4.13	8.2635	2.48	5.3	164.9
Jun	26.4	299.6	25.80	37.8	9.75	107.37	6.6	12.7	0.52	14.8	0.48	5.35	15.698	2.22574	3.13	11.648	2.56	5.5	165.6
July	25.1	298.3	23.89	52.1	12.44	102	5.3	12.6	0.42	14.9	0.42	4.70	15.428	1.64581	3.06	8.0954	2.48	4.5	139.6
August	23.4	296.6	21.57	62.7	13.53	85.9	6	12.4	0.48	15	0.46	5.18	15.079	1.67352	3.50	5.2358	2.38	4.0	124.5
Sep	22.9	296.1	20.93	62.0	12.97	53.69	6.7	12.1	0.55	14.8	0.50	5.59	14.978	1.88488	3.70	4.2824	2.35	3.9	116.3
Oct	21.3	294.5	18.99	53.0	10.06	53.69	8.5	11.8	0.72	14.2	0.61	6.46	14.656	2.61267	3.85	4.8041	2.26	4.1	128.4
Nov	20.4	293.6	17.97	49.5	8.89	59.06	9.3	11.6	0.80	13.1	0.66	6.46	14.478	2.98043	3.48	5.0544	2.16	4.0	119.3
Dec	19.0	292.2	16.47	58.2	9.59	64.42	8.5	11.5	0.74	12.5	0.62	5.80	14.204	2.64532	3.15	3.9593	2.10	3.4	105.8
Annual PET (mm/year) of the area																			1596.1

Potential Evapotranspiration calculated using Penman Combination method (Maichew)																			
Month	Parameters																		
	Temp (°C)	Temp (°K)	e _a (mm/d)	RH (%)	e _d (mm/d)	U ₂ (mile/d)	Sunshine hrs(n) (hr/d)	N (hr/d)	n/N	Ra (mm/d)	Fa(n/N)	RI(1-r) (mm/d)	ET ⁴ (mm/d)	R _o (mm/d)	H _T	E _{at} (mm/d)	Δ/□	PET (mm/d)	PET (mm/month)
January	13.7	286.8	11.74	67.5	7.92	59.1	7.1	11.6	0.6	12.8	0.5395	5.17903	13.192	2.31537	2.9	2.1241	1.59	2.6	79.9
Febura.	14.7	287.8	12.53	53.5	6.71	69.8	8.1	11.8	0.7	13.9	0.5856	6.10481	13.377	2.72866	3.4	3.46	1.64	3.4	95.4
March	16.1	289.3	13.71	60.9	8.35	69.8	7.2	12	0.6	14.8	0.532	5.9052	13.648	2.30919	3.6	3.1856	1.77	3.4	106.9
April	17.0	290.2	14.51	56.7	8.23	69.8	8.2	12.3	0.7	15.2	0.5733	6.536	13.819	2.54702	4	3.7308	1.91	3.9	117.0
May	18.1	291.3	15.55	47.9	7.45	75.2	8.8	12.6	0.7	15	0.593	6.67143	14.03	2.79046	3.9	4.9667	2.03	4.2	131.4
Jun	19.5	292.7	16.97	43.1	7.32	118.1	7.0	12.7	0.6	14.8	0.5017	5.56923	14.301	2.39678	3.2	7.3669	2.16	4.5	135.0
July	17.9	291.1	15.36	61.2	9.41	177.2	5.0	12.6	0.4	14.9	0.406	4.5374	13.991	1.67671	2.9	5.7765	1.97	3.8	119.1
August	17.5	290.6	14.98	66.5	9.96	134.2	5.4	12.4	0.4	15	0.43	4.8375	13.905	1.72433	3.1	4.1179	1.91	3.5	107.2
Sep	16.7	289.8	14.24	60.9	8.68	64.4	6.9	12.1	0.6	14.8	0.5136	5.70045	13.752	2.20355	3.5	3.2014	1.86	3.4	101.8
Oct	14.9	288	12.16	63.2	7.69	59.1	7.6	11.8	0.6	14.2	0.5593	5.95678	13.414	2.47644	3.5	2.489	1.69	3.1	96.5
Nov	13.8	287	11.82	60.7	7.18	59.1	7.8	11.6	0.7	13.1	0.5769	5.66801	13.219	2.58961	3.1	2.5839	1.59	2.9	86.6
Dec	13.1	286.2	11.29	61.6	6.95	59.1	7.8	11.5	0.7	12.5	0.5805	5.44239	13.082	2.61003	2.8	2.4135	1.49	2.7	82.6
Annual PET (mm/year) of the area																			1259.5

Table 4.10: Potential Evapotranspiration calculated using Penman Combination method

Table 4.11: Weighted AET of the study area

Class	Soil	Vegetation cover	AWCRZ	RD(m)	Area(km ²)	AET(mm/y)
1	Clay loam	deep rooted shrubs	250	1	584	1062.2
2	clay soil	moderately deep rooted(cereals & corn)	150	0.5	204	739.3
3	Clay loam	moderately deep rooted(cereals & corn)	200	0.8	17	1176.6
Weighted AET					805	982.8

Based on this calculation, weighted actual evapotranspiration of the study area is equal to **982.8mm/year**.

According to David.N, (1990) soil moisture budgeting is developed for humid climate and has less validate in arid and semi-arid zones and this work best for seasonal patterns of recharge, well developed soil which do not dry completely and when AET is similar with PET with relatively uniform precipitation. Therefore, for the application of water balance calculation in the study area the actual evapotranspiration estimated using Turc formula is more realistic than the water balance method suggested by Thorentwaite and matter.

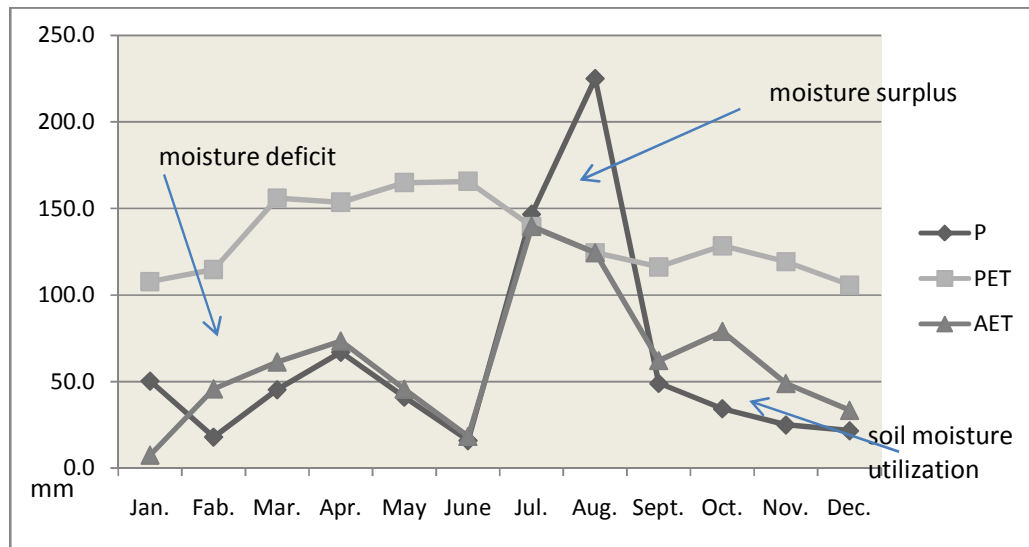


Figure 4.11: Thornthwaite Soil Water Balance of the area

4.9. SURFACE RUNOFF

Runoff is the component of stream water which is generated from precipitation as flowing water in a basin. Runoff occurs when the rate of precipitation exceeds the rate of infiltration in to a soil. Runoff from a given area due to rainfall depends on climatological and physiographical.

The climatological factors that affect the runoff are, type and form of rainfall, evaporation characteristic of the study area, and transpiration. The main physiographic factors on which the runoff characteristics depend on area and shape; average slope; the permeability of soil and geological characteristics like soil type, land use, position of rock layer and aquifer characteristics; And the presence of depression and natural reservoir in the area.

All streams other than Golina River in the study area are seasonal and intermittent hence they are not gauged and have not measured flow data. Therefore the runoff component for water balance of the area was determined using empirical formula of runoff coefficient method (rainfall-runoff relation).

The runoff coefficient is the fraction of rainfall converted in to runoff. This method estimates the runoff by multiplying the runoff coefficient to the rainfall depth of the area.

$$R = K * P$$

Where, R = runoff in mm

P = rainfall depth in mm

K = runoff coefficient

To estimate the amount of runoff from the surrounding hill to the valley floor is very difficult because there is no hydrometric measuring station in the area. The study of RVDP (1997) has tried to approximate the runoff proposed dam sites by using the historic discharge measurement of Golina River using the SCS model and regionalization approach. The other approach chosen was to approximate the runoff from the western escarpment through the use of the annual flow generated using SCS model for each proposed dam on RVDP. Accordingly the runoff coefficient of the mountainous area was approximated to range from 0.22 to 0.13. For estimation of the amount of runoff generated from the plains of the basin, the runoff coefficient is proposed by Co-SAERAR (1997) is 0.10.

Table 4.12: The annual rainfall and surface outflow from the basin

Part of the study area	Rainfall (mm/y)	Area (km ²)	Rainfall (Mm ³ /y)	Estimated annual runoff (Mm ³ /y), 10%, 13% & 22% of precipitation were assumed for the valley, escarpment and highland respectively
The valley floor	739	140	103.5	10.4
The valley Escarpment	739	144	106.4	13.8
The Highland	844	527	435.8	95.9

Since the sediment in the western margin of the valley is coarser and highly permeable it would be reasonable to assume about 20-30 % (RVDP, 1998) of the runoff generated from the high lands and escarpment infiltrates to recharge the groundwater.

Therefore, the total amount of runoff that leaves the project area is the sum of surface inflow from the high lands and surface runoff from the plain during *Kiremt* and the *Belg* rain season and estimated as 98.4MCM.

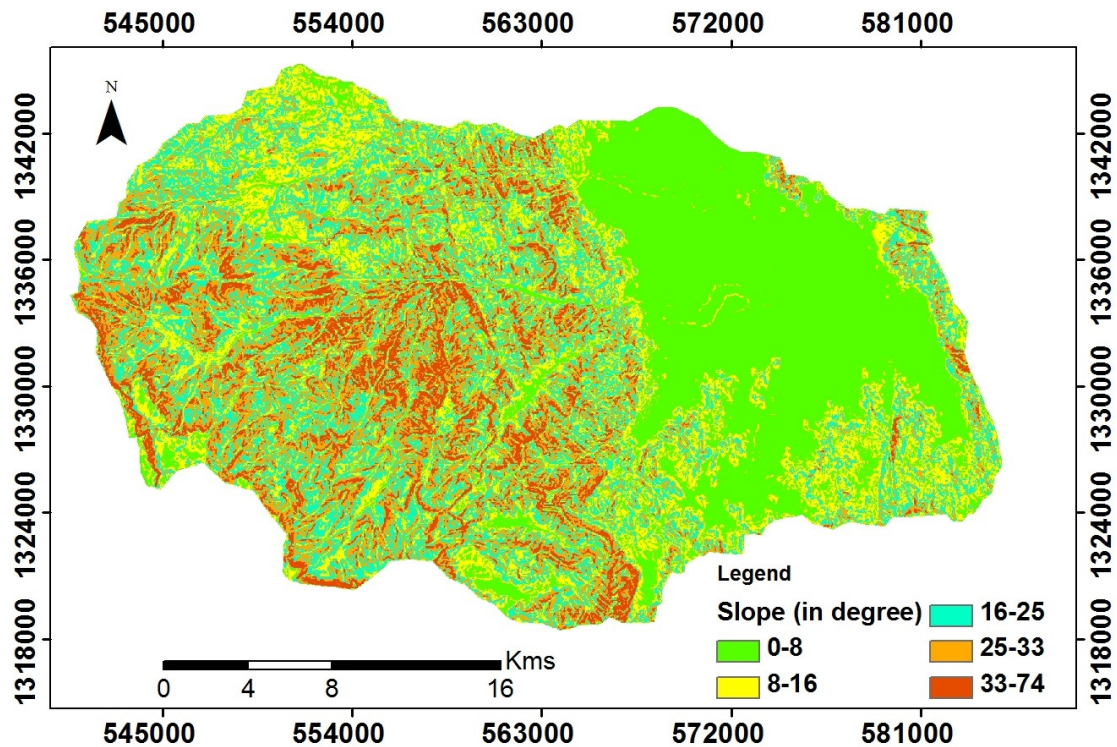


Figure 4.12: Slope map illustrating the topographic gradient

CHAPTER FIVE

5. HYDROGEOLOGY

5.1. INTRODUCTION

Groundwater is difficult to visualize. Some people believe that groundwater collects in underground lakes or rivers. In fact, groundwater is simply the subsurface water that fully saturates pores or cracks in soils and rocks. Such conditions may exist in cavernous limestone or lava rock, but they are relatively uncommon. Most groundwater is contained in and moves through the pore spaces between rock particles or in fractures and fissures in rocks. When the pore spaces in sand and gravel become saturated with water, the water is called groundwater.

Groundwater is replenished by precipitation and, depending on the local climate and geology, is unevenly distributed in both quantity and quality. When it rains, some of the water runs off to streams, some evaporates, and some recharges aquifers (Moore et al., 1995).

Groundwater is stored and transmitted by aquifers. An aquifer may be a layer of gravel or sand, sandstone, limestone, lava flow, or fractured granite. The major productive aquifers in the world are unconsolidated sand and gravel, limestone, dolomite, basalt, and sandstone. The location and yield of aquifers are dependent on geologic conditions, such as the size and sorting of grains in unconsolidated deposits and faulting, solution openings and fracturing in consolidated rocks.

Two properties of aquifers that affect the storage and flow of groundwater are porosity and hydraulic conductivity (Freeze and Cherry, 1979).

The quantity of water that a given type of soil, sediment, or rock will hold depends on the porosity of the formation. Porosity is a measure of pore space between the grains of the rock or of cracks in the rock that can fill with water.

The distribution of permeability and porosity is related to the characteristics of the rocks. This is important when explaining the hydraulic properties and when choosing sites for drilling wells to exploit groundwater resources. In this research work, in order to identify different hydrogeological units the available data (geological and geophysical information,

meteorological, bore hole, pumping test, remote sensing data, etc) are interpreted and the area is classified into different hydrogeological units.

5.2. REVIEW OF RESISTIVITY SURVEY VALUES IN THE STUDY AREA

The groundwater study in the valley was supported with geophysical surveys since the work of German Consult in 1976. Later survey conducted by Co-ASERAR 1997, Geo-Engineering Service (GES) 2003 and Metaferia Consulting Engineers 2009. The survey were aimed at determining the thickness of loose sediment, and depth to ground water and delineating probable zones of saturated aquifer, and fracture or fault zone of bed rock.

Metaferia Consulting Engineers was conducted along a traverse with Vertical electrical sounding, the traverse runs from South Kobo-Gedemeyu, and South Gedemeyu through Hormat- Golina interfluves to Ulaga (Figure 5.1).

The VES points are arranged into pre-defined profile lines as shown in Figure 5.1. The electrode spreading of VES survey points was mostly in N-S direction anticipating almost homogenous sediment thickness for current transmission.

The results of this geophysical exploration as explained in the Metaferia Consulting Engineers final report, 2009 The VES points in each profile line are separated mostly at one km interval in the W-E direction and sometimes up to 2 km. Correlation of resistivity values are made in the VES points laying the same profile lines to produce geoelectrical section. In the production of geo-electric section the ranges of the resistivity values are physically interpreted as follows:

- 15 Ohm-m and at the top : top soil
- 0-15 Ohm-m: clay layer
- 16 – 50 Ohm-m: sand/gravel layer
- 20 – 200 Ohm: weathered volcanic/sandy-gravelly layer
- > 200 Ohm-m: bedrock

The interpreted data along the profile line helps to have information on the total sediment thickness, clay layers, aquifer zone and weathered zone. The interpretation of each profile lines is summarized in Table 5.1.

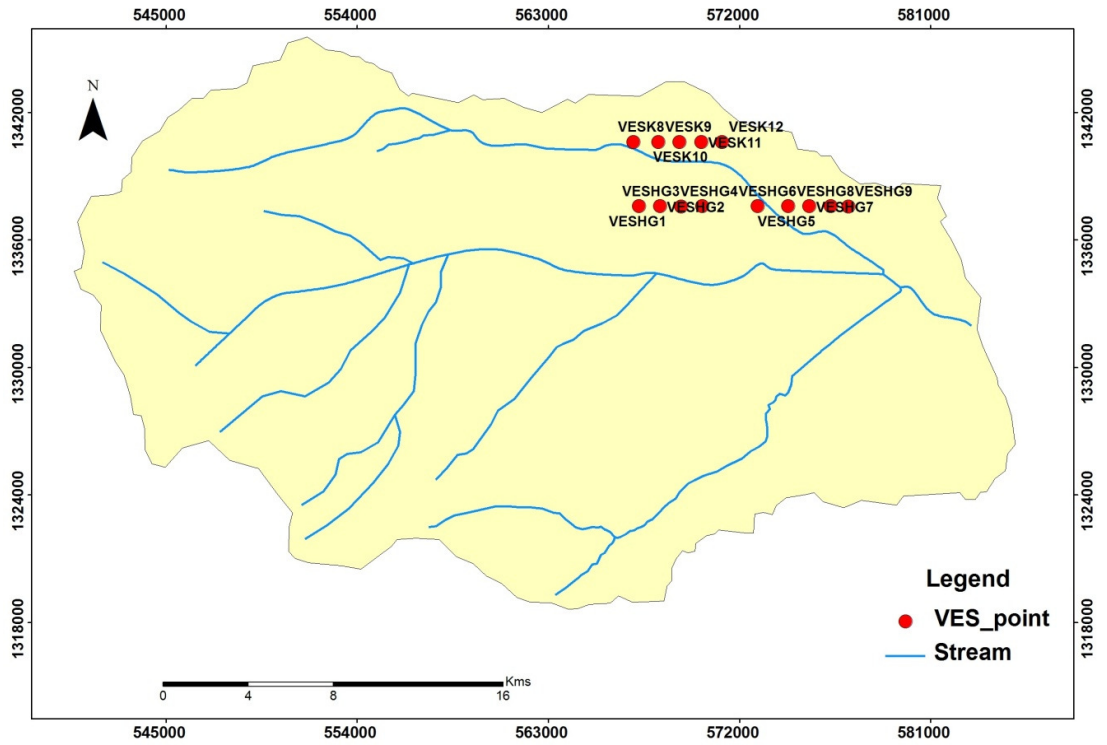


Figure 5.1: Location map of VES points along the profile lines in Kobo Valley (modified from Metaferia Consulting Engineers, 2009).

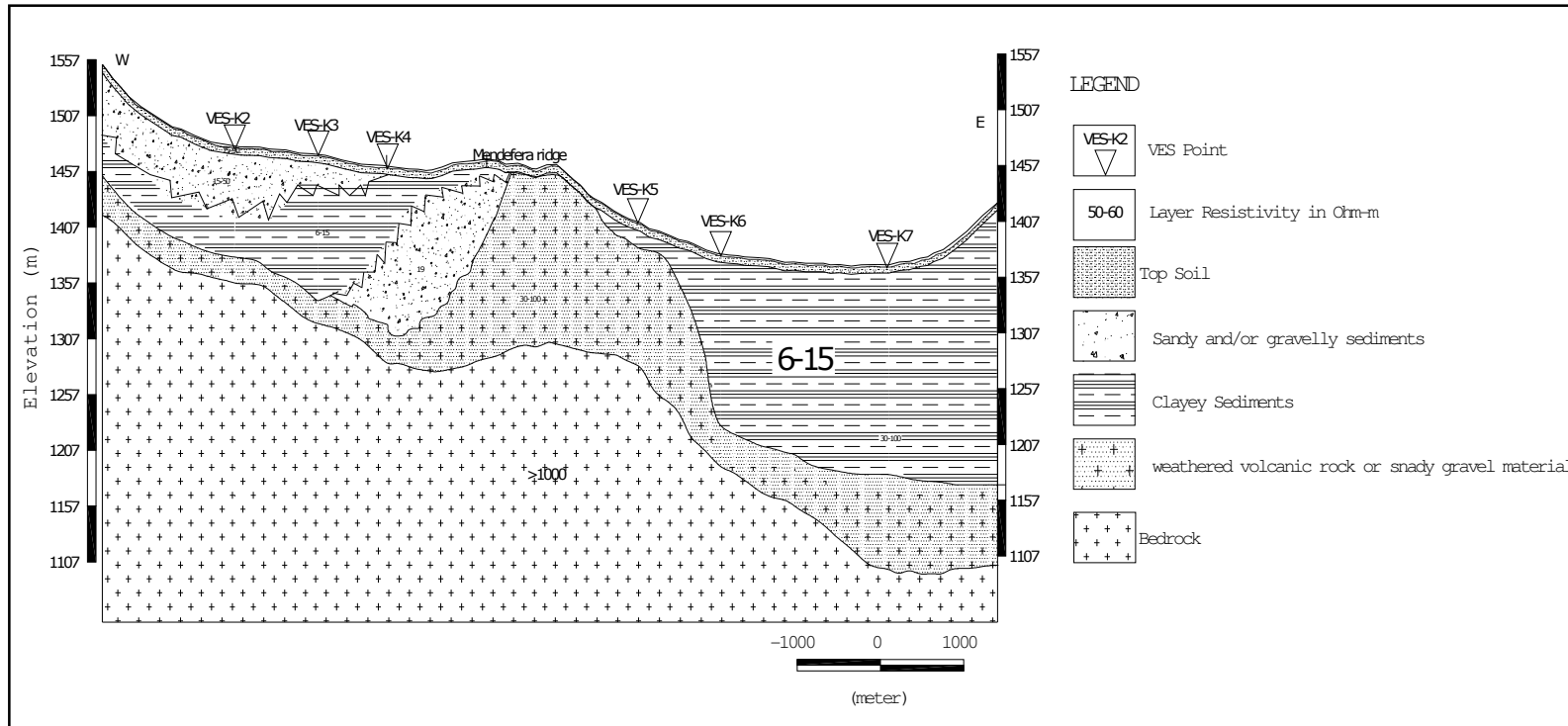


Figure 5.2: Geoelectric Section along Profile K1, 10.75km long West-East direction from (566998E, 1345418N) to (577741E, 1345443N), Kobo (Metaferia Consulting Engineers, 2009)

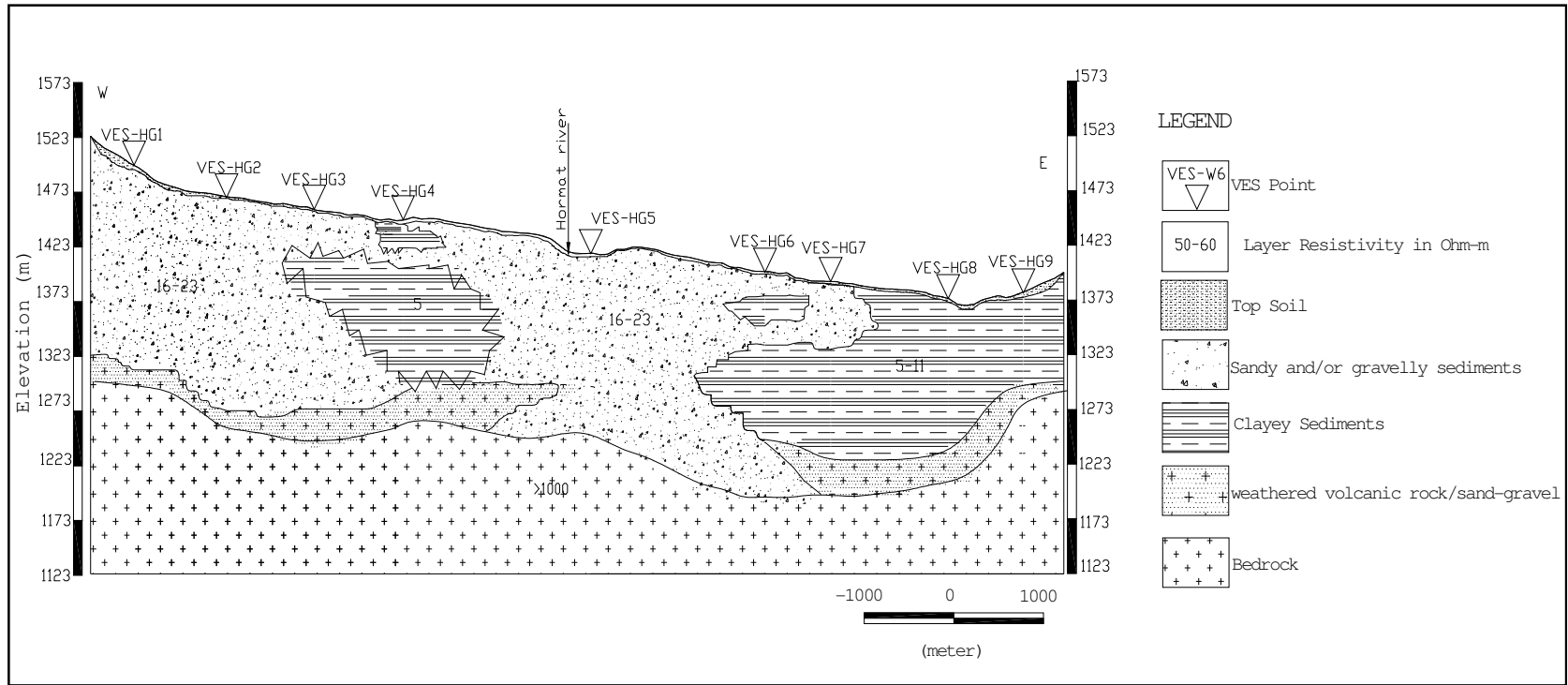


Figure 5.3: Goelectric Section along Profile K3 10.87km from (566671E, 1337462N) to (577720E, 1337462N), Hormat -Golina, Kobo (Metaferia Consulting Engineers, 2009).

5.3. AQUIFER CHARACTERISTICS

The nature and distribution of aquifers and aquicludes in a geologic system are controlled by the lithology, stratigraphy and structures of the geologic deposits and formations (Freeze & Cherry, 1979). The aquifer system in the study area could be broadly classified as the unconsolidated sediment aquifers and volcanic aquifers. The unconsolidated sediment aquifers have mainly occupy the valley floor where as the volcanic aquifers mainly constitute the escarpments and plateau. Classification was done from the information of surface geology, borehole lithologic log data, and pump test data. Based on these information major units are described below.

5.3.1. UNCONSOLIDATED SEDIMENT AQUIFERS

Fault block valleys are created by down-dropping of large crustal pieces along faults. Erosion of the mountains creates sediments that is carried in to the valley, forming talus slopes, alluvial fans, and alluvial and lacustrine deposits (Fetter, 2001). The sediments like alluvial fan gravels, and channel deposits can be very coarse, with high hydraulic conductivities and lacustrine clays, on the other hand can be fine, with low conductivity. Gravel aquifers confined by lacustrine sediment are quite typical of such basins (Fetter, 2001). According to Fetter, in semiarid to arid region groundwater is recharged by precipitation in the mountains, bed rock beneath the mountains may receive direct recharge and the feed the valley-fill sediments. Stream originating in the mountains may also lose water to the alluvium when the flow goes across the valley bottoms.

The Quaternary sediments occupy an area of 184sq.km of the study area. The floor of Kobo valley is a flat plain with decreasing slope from west toward east and it is filled with quaternary deposits derived largely from volcanic mountain ranges that are standing high on the shoulders of the valley. Geological logs of the boreholes and the geophysical surveying results of CoASEARAR (1997) show that the thickness of the sediments of the basins vary from about 300 m in the east to less than 50 m near the mountains to the west (Figure 5.6). The western part of the valley is characterized by coarse sediments while the deposit becomes finer towards east.

The Quaternary sediment deposits have been subdivided into different Hydrogeological units and the short description is indicated bellow.

5.3.1.1. QUATERNARY COLLUVIAL AND ALLUVIAL DEPOSITS

Quaternary colluvial deposits mainly found at the foot of the western escarpment. The materials are mainly derived from down slope movements, fall and flow of fragments

derived from weathering and erosion owing to the gravitational attraction. This deposit has a characteristic loose, incoherent and coarse to fine-grained deposits collecting on slopes by gravity. Their compositions are clay, silt, sand and gravel, pebbles, cobbles and boulders. The coarser materials are the most important aquifers through which groundwater movement is effected very easily and clay layers acts as impervious layer.

Quaternary alluvial deposits are also found at the mouth and also along the section of rivers draining the western escarpment. They are good aquifers and acts from their geographic location as a good recharge zone (Figure 5.4.).

5.3.1.2. INTERFLUVIAL, FAN FOOT PLAINS AND VALLEY BOTTOM QUATERNARY DEPOSITS

This is the major type of unconsolidated material covering most part of the valley floor. It is dominantly composed of sandy silty clay and covers valley bottom of major streams, and foot hills. This deposit has low to high productivity based on the abundance of clay material. This situation has resulted in the heterogeneity of the aquifer and hence its hydraulic conductivity is dependent on the position within the geologic formation. This material is mainly aquitards forming a multilayered aquifer locally (Figure 5.5).

5.3.1.3. CENTRAL VALLEY FLOOD PLAIN QUATERNARY DEPOSITS /LACUSTRINE DEPOSIT

This unit is mainly composed of clay deposits and covers mostly the central and eastern part of the valley fill. CoASEARAR, 1997 stated that the geophysical investigation results indicate an existence of low resistivity (<10Ωm) horizon at greater depth (>100m) that interpreted to be fine grained sediment deposit or/and saline groundwater zone. Water sample from Hurte densa village (TW3 well) which is relatively deeper well has higher electrical conductivity which could be the influence of the deeply located horizon of high salinity groundwater from the lacustrine deposit. Hydrogeologically this zone is classified as poor or low productivity zone; it is mainly aquicludes.

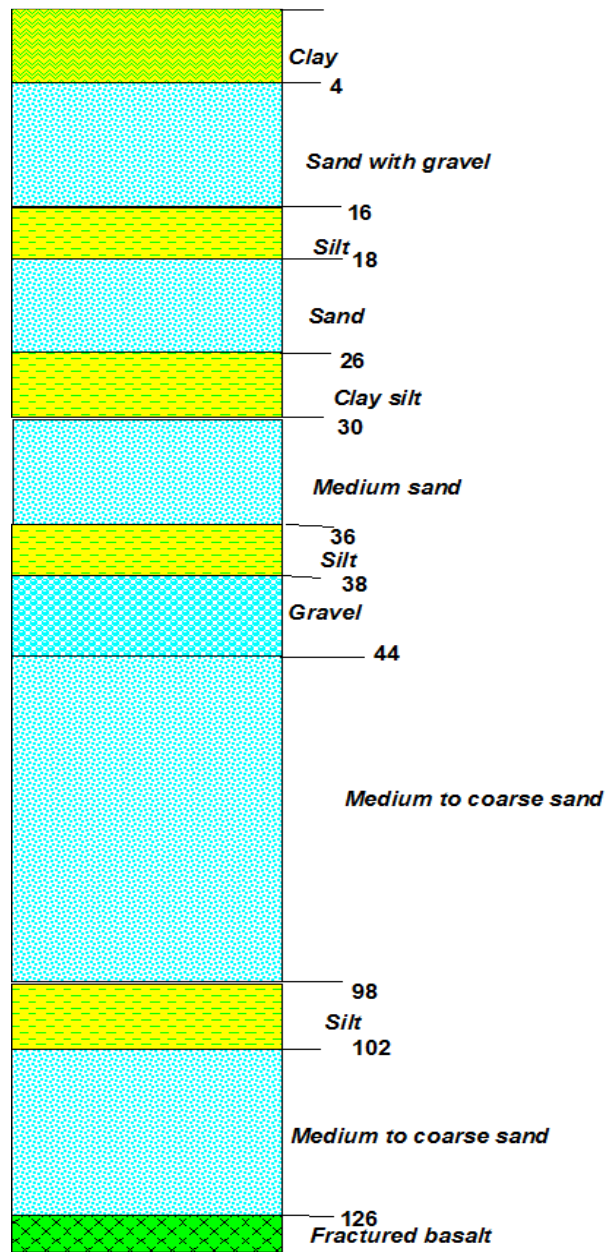


Figure 5.4: Vertical distribution of aquifer from well log of PHG1 located on the western side of the valley (Quaternary colluvial and alluvial deposit), with the transmissivity values of $>1000\text{m}^2/\text{d}$, hydraulic conductivity of $33\text{m}/\text{d}$ and give yield of $50\text{l}/\text{sec}$. (Modified from Metaferia Consulting Engineers, 2009)

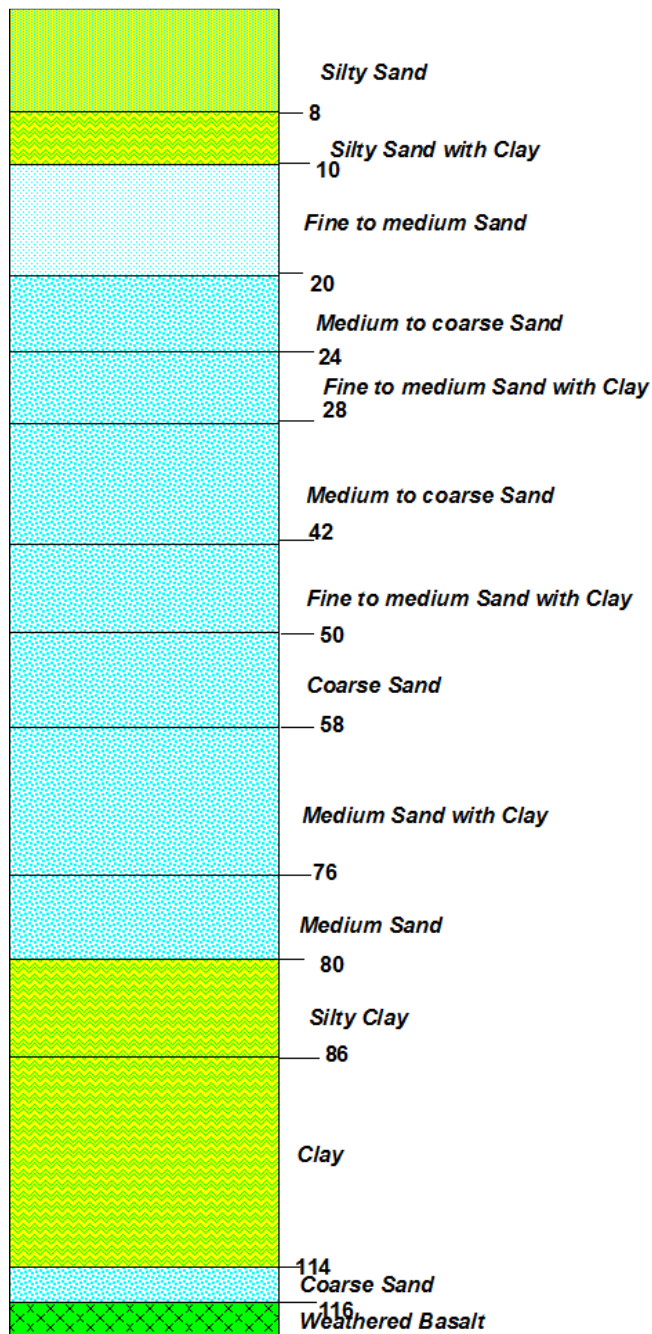


Figure 5.5: Vertical distribution of aquifer from well log of THG1 located at the central part of the valley (valley bottom Quaternary deposits), with low transmissivity and medium hydraulic conductivity, 164m²/d and 5.47m/d respectively and a yield of 32l/sec. (Modified from Metaferia Consulting Engineers, 2009).

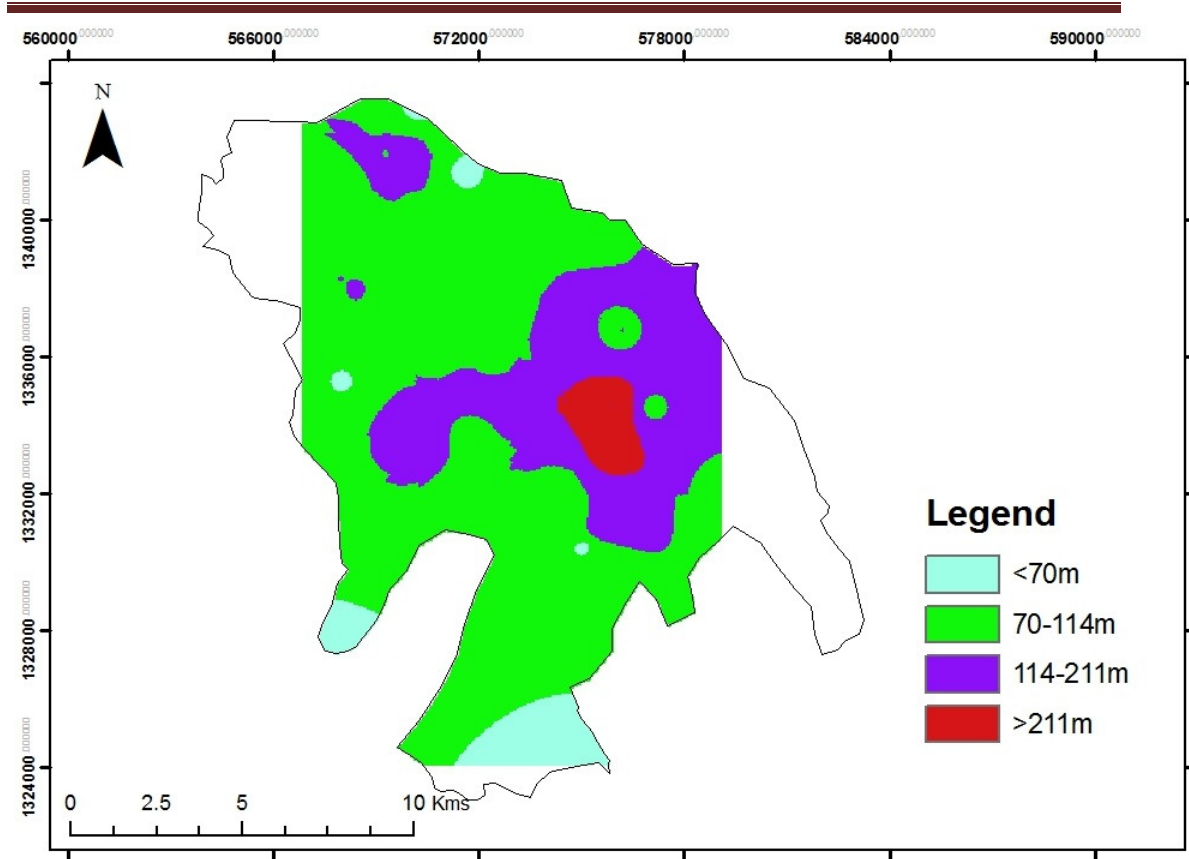


Figure 5.6: Spatial variation of sediment thickness through the valley (prepared from lithological log of boreholes)

5.3.2. VOLCANIC ROCK AQUIFERS

The storage and transmission of groundwater in the volcanic rocks largely depends on type of porosity and permeability formed during and after the rock formation. This group includes various lithological units belonging to different series, but from the hydrogeological point of view, they are grouped together and described here as the volcanic aquifers. Basalt, rhyolite, basic and acidic pyroclastics that comprise ignimbrite, tuffs and volcanic agglomerates are from the bulk of this unit. Due to the prevailed tectonic events in the past, this formation is moderately to highly fractured.

The volcanic rock that forms step and elevated mountainous terrain position has a very limited recharge capacity resulting high surface run off in the Kobo valley. This recharge-discharge condition in the elevated volcanic is revealed by the absence of high yielding springs in the immediate escarpment zones and foot hills bordering the Kobo plain. However, as one goes further to the west the aquifers property of the basalt changes. Several large springs emanate from big fractures and join together to form Perennial River

of the valley. The volcanic rocks in the area are also the basal formation beneath the alluvial cover, in some cases they are encountered at shallower depth but later alteration has filled the fractures with secondary minerals making them poor aquifers.

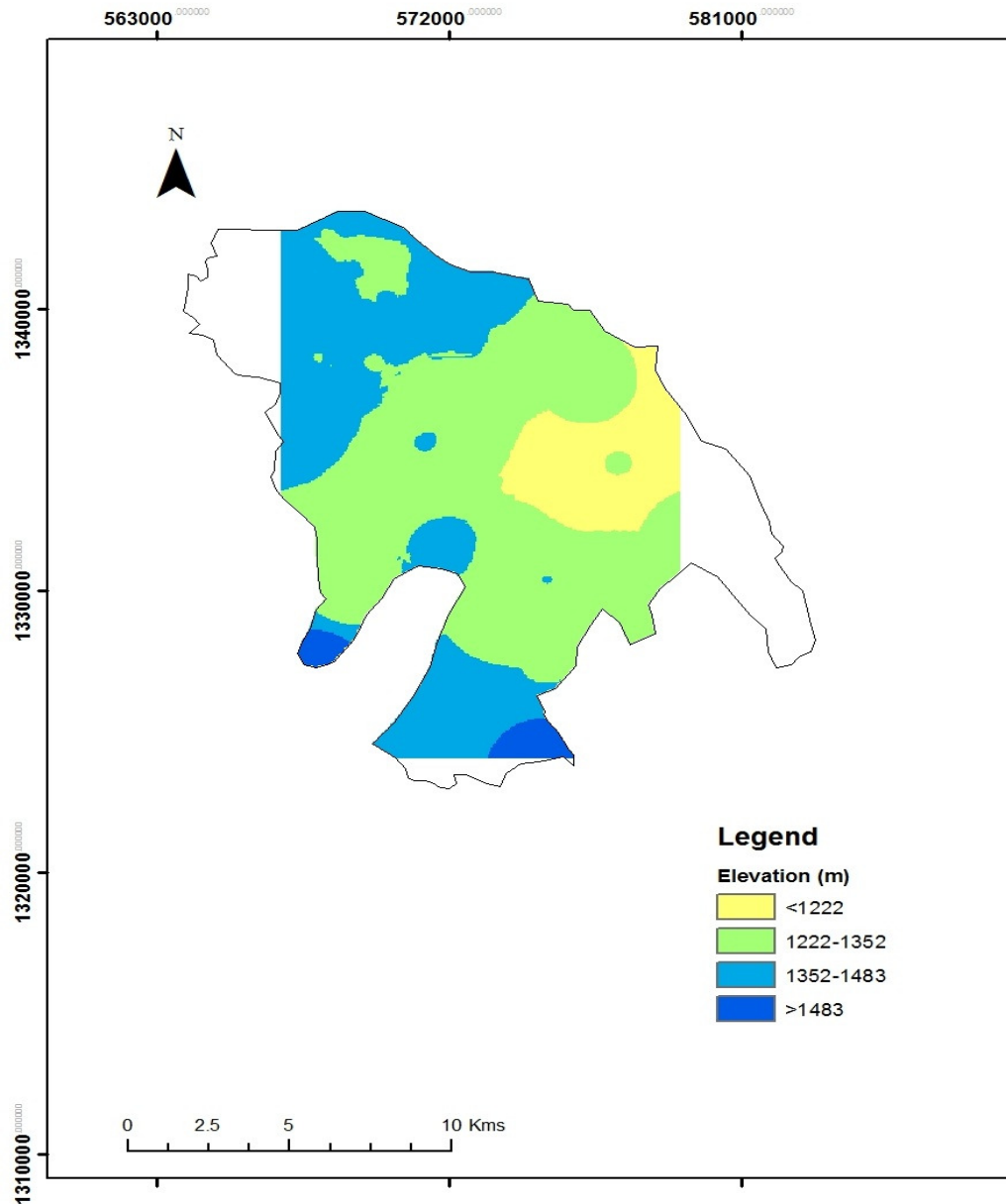


Figure 5.7: Bed rock elevations beneath the alluvium fill deposit in Kobo valley (prepared from lithological log of boreholes)

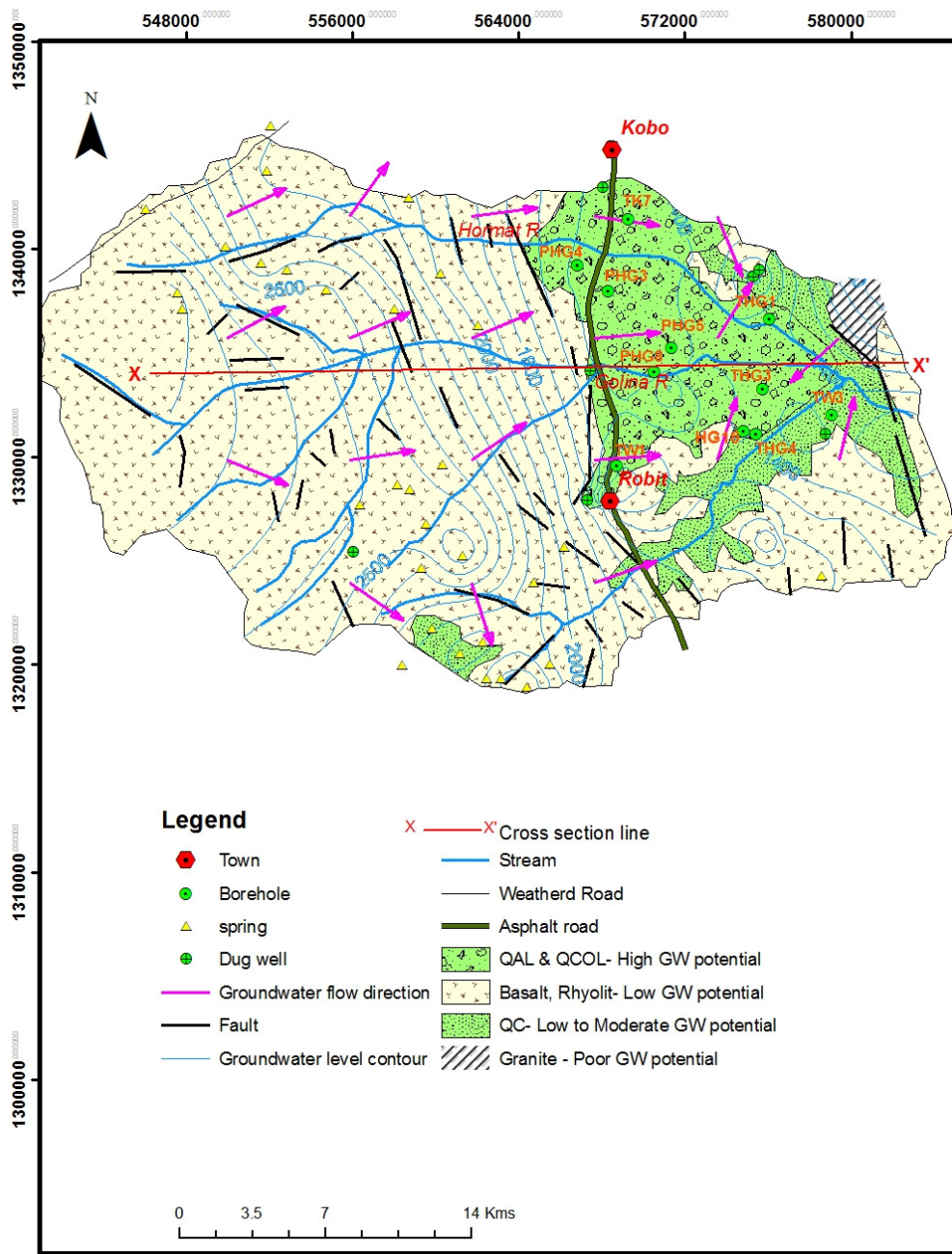


Figure 5.8: Hydrogeological map of the area

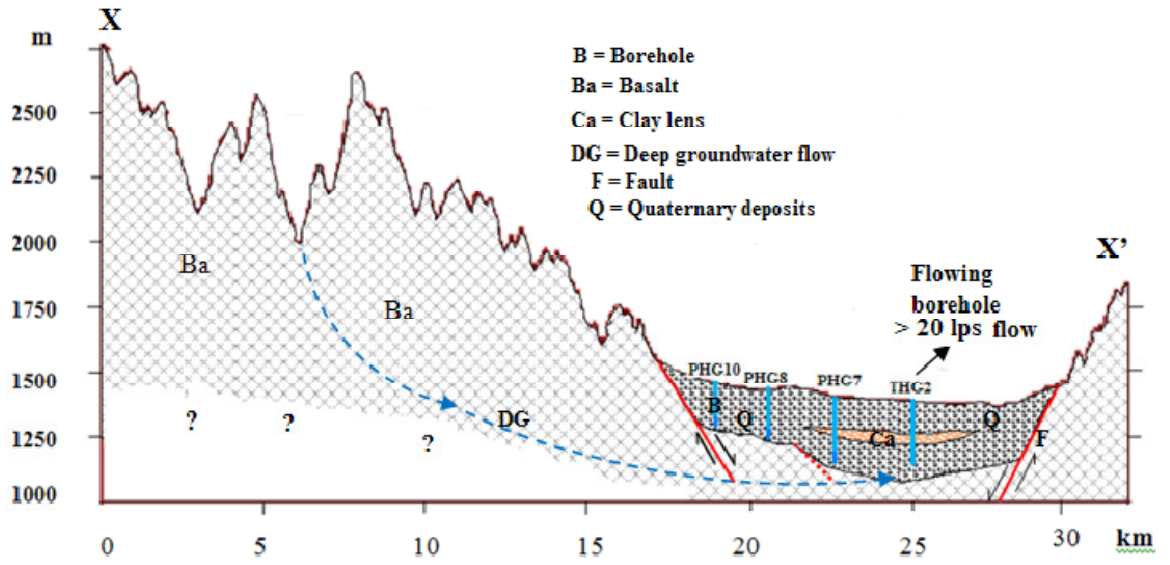


Figure 5.9: Hydrogeological cross-section (West – East)

Table 5.1: Summary of VES survey data interpretation (After Metaferia Consulting Engineers, 2009)

No.	Traverse line	VES point	sediment thickness (m)		Range of weathered zone thickness	Layer and lithology identified
			Max.	Min.		
1	K2: South Kobo-Gedemeyu: UTM 1340604N 567020 to 571191E, 11 km in the W-E direction	VES-K8 to K12	195 m at VES-K11	94 at VES-K12	20 to 30 m all along the profile line	The sandy-gravelly layer at VES-K8, VES-K10, VES-K11 and VES-K12 and the thickness of varies from 105 m at VES-K8 to 45 m at -K11, the second layer is the clay layer filling the central and eastern part of the profile is 105 m to 149 m at VES-K11. weathered zone has thickness of 20 to 30 m
2	K3: South Gedemeyu through Hormat-Golina interfluves to Ulaga: UTM 1337578 N 566671E to 577720E 14km in the W-E direction	VES-HG1 to HG9	217 m at VES-HG3	84 m at VES-HG9	5 to 10 m	First sand/gravel layer with maximum thickness of 195 m at VES-HG2 and minimum thickness at VES-HG4 (10 m), second layer, thick clay patch under of max 150 m at VES-HG7 and 114 m at VES-HG4, third layer above the fresh bed rock is the weathered zone.

5.4. GROUNDWATER HYDROLOGY

The occurrence and movement of groundwater are related to physical forces acting in the subsurface and the geologic environment in which they occur. This section presents a groundwater dynamics of the study area and hydraulic properties of the aquifers.

5.4.1. GROUNDWATER FLOW DIRECTION

Maps of the water table for unconfined and of the potentiometric surface of confined aquifer are basic tools of hydrogeologic interpretation. These maps are two dimensional representations of three dimensional surfaces.

Potentiometric surface is a surface of equal hydraulic heads or potentials, typically depicted by a map of equipotentials such as a map of water-table elevations. The data used to construct water-table and potentiometric-surface map are water level elevations as measured in wells and springs.

In area where the water table or potentiometric surface has a shallow gradient, the groundwater contours will be spaced well apart. If the gradient is steep the groundwater contour will be closer together. Groundwater will flow in the general direction that the water table or potentiometric surface is sloping (Fetter, 2001).

A groundwater flow line is an imaginary line that traces the path that a particle of groundwater would flow as it flows through an aquifer. Flow lines are helpful for visualizing the movement of groundwater. Flow lines will cross equipotential lines at right angles.

The groundwater contour map Figure 5.10 of the area was constructed using the field inventory data that have static water level and elevation above sea level.

Groundwater movement in the Kobo valley is controlled by the morphology of the valley bottom and the major Golina outlet which are created due to E-W trending transversal faults with respect to the main rifting direction. The general groundwater flow direction in the entire valley is from west to east except that there are localized flow components observed in the vicinity of elevated hills, boundaries of the basin and along the river banks Figure 5.11.

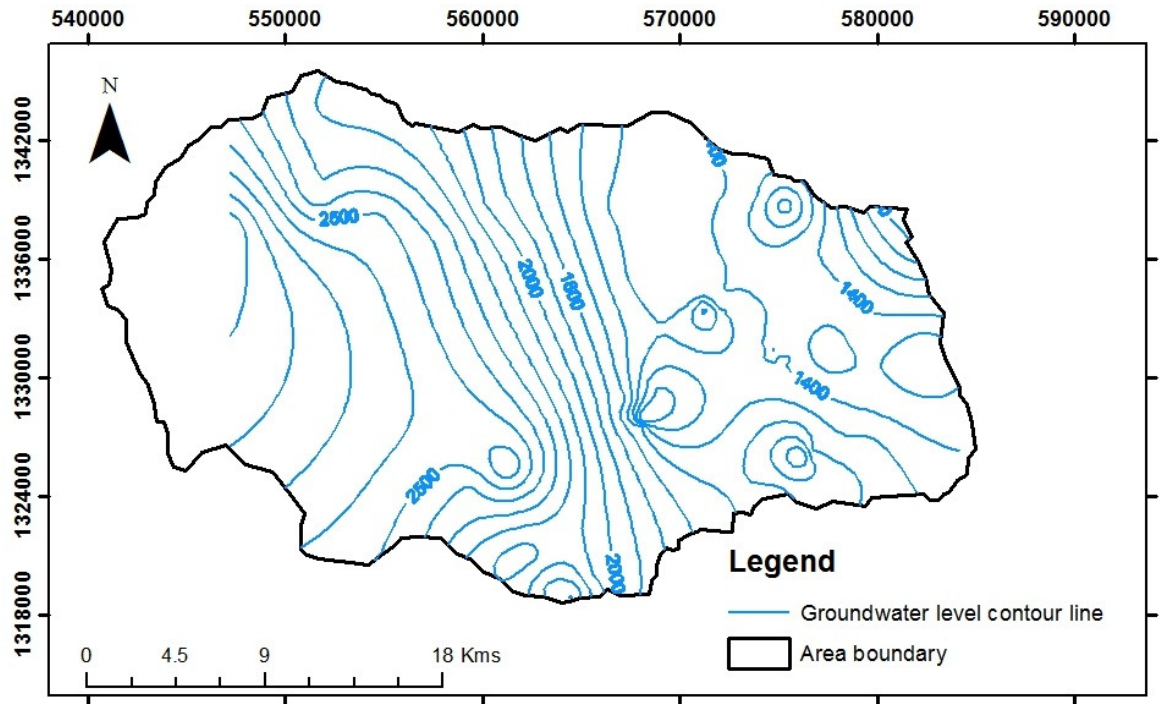


Figure 5.10: Groundwater level contour map (equipotential surface map)

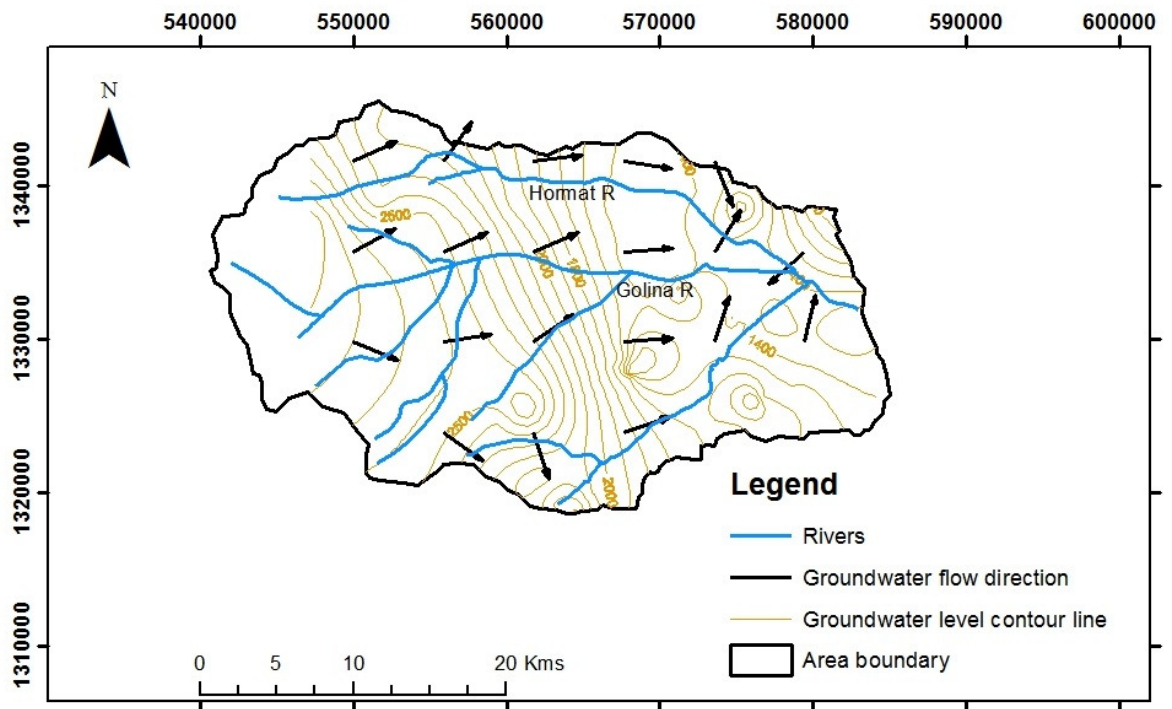


Figure 5.11: Groundwater level contour map show interpreted groundwater flow directions

5.4.2. GROUNDWATER RECHARGE-DISCHARGE MECHANISM

Recharge can be broadly defined as water that reaches an aquifer joining the water table from any direction, which contributes an addition to the groundwater reservoir. There are three principal mechanisms of recharge defined by Sophocleous (2004) as:

- *Direct or diffuse recharge:* water added to the groundwater reservoir in excess of *soil-moisture deficits* and evapotranspiration, by direct vertical percolation of precipitation through the unsaturated zone: that is, recharge below the point of impact of the precipitation. It is typical of humid climates because frequent, regular precipitation maintains a high water content in the soil, so that there is little additional storage capacity in the vadose zone.
- *Indirect recharge:* results from percolation to the water table following runoff and localization in joints, as ponding in low-lying areas and lakes, or through the beds of surface water courses.
- *A localized or focused:* resulting from horizontal surface concentration of water in the absence of well-defined channels, such as recharge through *depressions, joints and faults*.

In arid and semi-arid regions, localized and indirect recharges are often the most important sources of natural recharge.

The above mechanisms usually do not occur individually rather in combination which makes the assessment complex. On the other hand, the recharge and discharge conditions of an area is controlled by several factors, Close evaluation of climate, topography, drainage, geological framework, hydrochemical trend, land use/land cover and Piezometric patterns are equally important in classification of the area into recharge and discharge zones.

Due to the relative higher annual PET over the total annual precipitation in the flat plain (graben), direct recharge from precipitation is rare. Recharge in the graben from precipitation seems during sporadic torrential rain falls because the water balance in the Kobo station shows no surplus water for recharge.

During intensive rainfalls in the western highland escarpment, Hormat and Golina rivers causes flooding covering large area of the plane for weeks (see figure 5.12). However the relative thick layer of lacustrine consists of clay, silt and sand intercalation (central and eastern part of the graben) reduce direct recharge/ infiltration in to the groundwater table. However, the contribution of tectonic structure particularly fault/fractures that cross east to west of the study area may have significant role in downward movements of water from

water bodies, accumulated during flood period particularly at the downstream Hormat and Kelkeli river where the surface runoff is lost quickly in the plane before joining the ultimate discharge through the Golina gorge to the Afar depression.

Fault zones can act either as barrier to groundwater flow or as groundwater conduits depending up on the nature of filling material in the fault zone and orientation of the fault lines, particularly faults in poorly consolidated rocks with low displacement exhibited good permeability (Fitter, 2001). In the study area there exist a number of faults which can acts both as barriers or conduits in groundwater flow. Joints and deep fault lines trending NNE-SSW, ENE-WSW from Zoble ridges and N-S from Lasta Mountains dipping towards the lacustrine sediment plane are expected to act as conduits for groundwater flow from highland escarpment. Tectonic discontinuity and associated fractures of the escarpment is a potential recharge zone for deep aquifer system of the plane. Sileshi Mamo (2007) observed that Deep thermal groundwater with temperature exceeding 42°C suggests that it has traveled to a depth exceeding 689m from recharge area and is the oldest, which show regional groundwater discharge.



Figure 5.12: Photo shows flood plain after torrential rainfall on Eastern part of the graben. Recharge areas are usually in topographic high places; discharge areas are located in topographic lows. In recharge area, there is often a rather deep unsaturated zone between the water table and the land surface. Conversely, the water table is found either close to or at the land surface in discharge area (Fetter 2001).

Toth(1963) showed the possibility of mapping recharge and discharge areas on the basis of field observation using the basic indicators such as topography, peizometric patterns,

hydrochemical trends, environmental isotopes, and soil and land surface features. Among these indicators, topographic elevation is the simplest (Freeze and Cherry, 1979) and piezometric measurements are the most direct.

Flow lines on a flow net tend to diverge from recharge areas and converge towards discharge areas. A Water - table contour map can often be used to locate groundwater recharge and discharge areas (Fetter 2001). The groundwater contour map Figure 5.13 clearly shows zone of convergence and divergence. The diverging groundwater flow lines from the highland towards the graben suggesting that the eastern and western part of the area are recharging zones while the graben situated at the foot of the highlands is discharging zones.

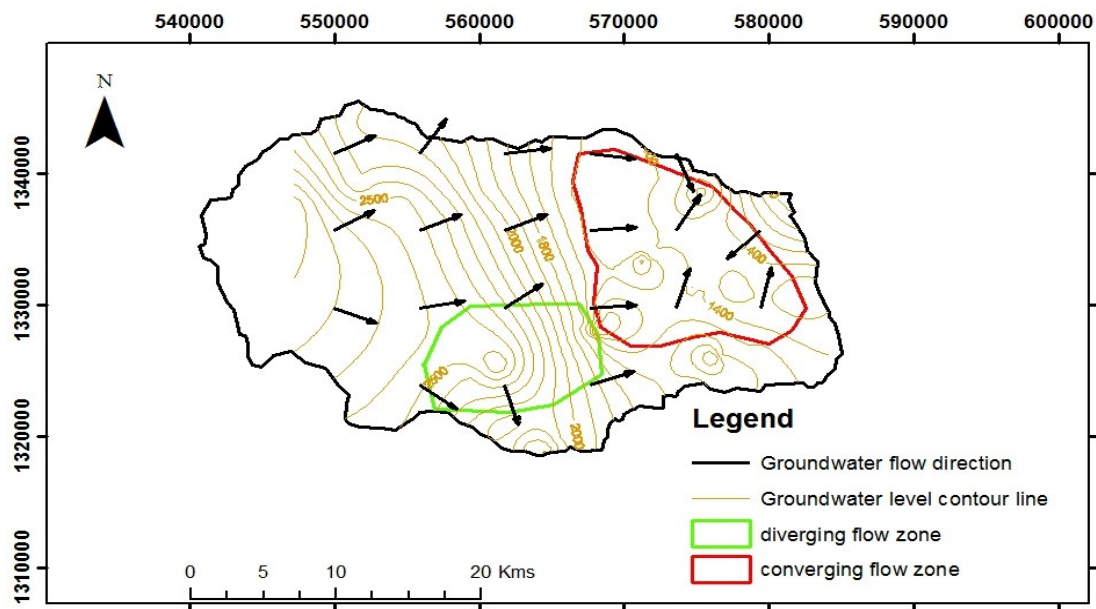


Figure 5.13: Converging and diverging flow zones, associated with discharge and recharge areas respectively and drawn on groundwater level contour lines.

5.4.3. GROUNDWATER AND SURFACE WATER INTERACTIONS

Groundwater and surface water are not isolated components of the hydrologic system; instead interact in a variety of physiographic and climatic landscapes (Sophocleous, 2004).

In many regions groundwater 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 resources, can therefore affect the other.

Groundwater and surface water bodies such as rivers most of the time interact in such a way that they are gaining, losing or acting as both. In arid regions, many rivers are fed by overland flow, interflow and base flow at high altitudes. As they wind their way to a lower elevation, the local rainfall amount decreases, consequently, there is less infiltration and a lower water level elevation. There may also be a dramatic change in the depth of groundwater when a stream draining a high altitude basin of lower permeability material flows out on to coarse alluvial materials. For whatever reasons, if the bottom of the stream channel is higher than the local water table, water may drain from the stream in to the groundwater at depth. As one goes down stream of a given river of such a type, less and less water will be found in the channel. This is a losing or influent stream. The rate of water loss is the function of the depth of the flowing water and the permeability of the underling alluvium. Fine grained alluvial deposits on the channel will retard the rate loss in to the groundwater (Fetter 2001).

Interaction of the groundwater and streams can be evidenced by observations of groundwater flow direction (vector) overlapping with the drainage network (see figure 5.14 below). Golina River and its tributary have a behavior of gaining from the aquifer in the downstream.

In the GES, 2003 appraisal report estimated recharge through the river channel of main rivers (Golina, Hormat and Kelkeliti) to be 6.26MCM and from runoff of remnant hills 0.6 MCM. However, the current study showed that no recharge from rivers to the groundwater rather the groundwater feeds the river.

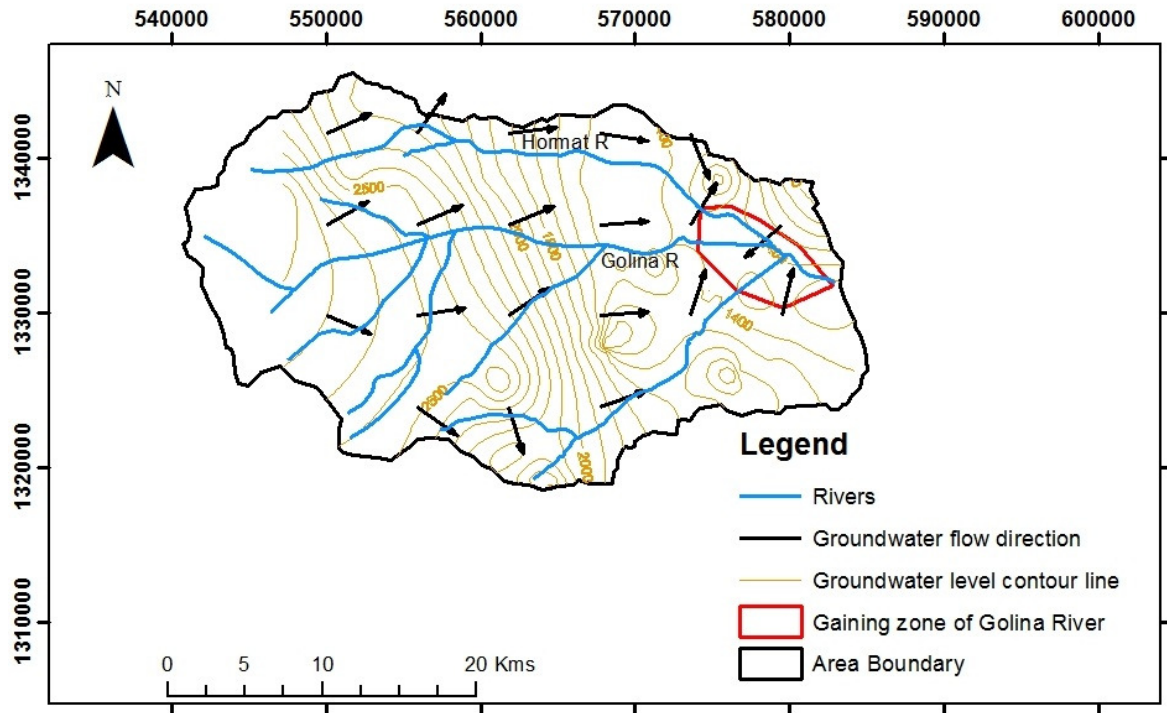


Figure 5.14: Gaining zone map of Golina River and its tributaries, indicating groundwater and surface water interactions

5.5. HYDRAULIC CHARACTERISTICS OF AQUIFERS

5.5.1. FIELD INFORMATION

The water bearing materials in the study area are mainly Quaternary alluvial and colluvial deposits with fractured and weathered basalts. The total number of wells inventoried in the study area is more than 90 and out of them Forty one wells have relatively full pumping test data including geological descriptions. In this section those wells with pumping test data have been given the main emphasis in analyzing the aquifer system. The data were compiled by different governmental and nongovernmental organizations such as Kobo-Girana Valley Development Project, Metaferia Consulting Engineers, Tana Drilling, and China Geo-Engineering.

The duration of the pumping test in each well is variable, ranging from 1320 minutes on HG2 to 4320 minutes. As shown from the data, there is not that much draw down in most of the wells and the recovery was, thereafter, fairly rapid. The analyses of the test depended on the type of aquifer, the nature and the degree of penetration of the pumped well into the aquifer and other factors.

The pumping test methods ideally require water level data from observation wells. 18 wells have one or more observation wells used for water level measurement. The method used for data analyses thus depends on the type of aquifer and how best the mathematical curves underlying the various interpretation methods match the field data. In applying the methods, water level measured on the pumping wells the distance to the observation well, in fact, is replaced with the distance from the rim of the casing to the centre of the well.

5.5.2. TYPES OF AQUIFER

Calculating hydraulic characteristics would be relatively easy if the aquifer system (i.e. aquifer plus well) were precisely known (Kruseman and Ridder 1994). Interpreting a pumping test is primarily a matter of identifying an unknown system. System identification relies on models, the characteristics of which are assumed to represent the characteristics of the real aquifer system.

Identification of the aquifer system of the area was performed using three integrated approaches;

- By carefully observing the lithological log of the wells,
- By construction of diagnostic plots (log – log plots) and specialized plots (semi – log plot) of drawdown vs time and,
- By observing the static water level with respect to the position of water bearing formation.

A geologic log is constructed from sampling and examination of well cuttings collected at frequent intervals during drilling a well or test hole. Such logs furnish a description of the geological character and thickness of each stratum encountered as a function of depth, thereby enabling aquifers to be delineated (Todd 2004). It is the most important way of knowing the aquifer system than the others but preparation need careful follow up.

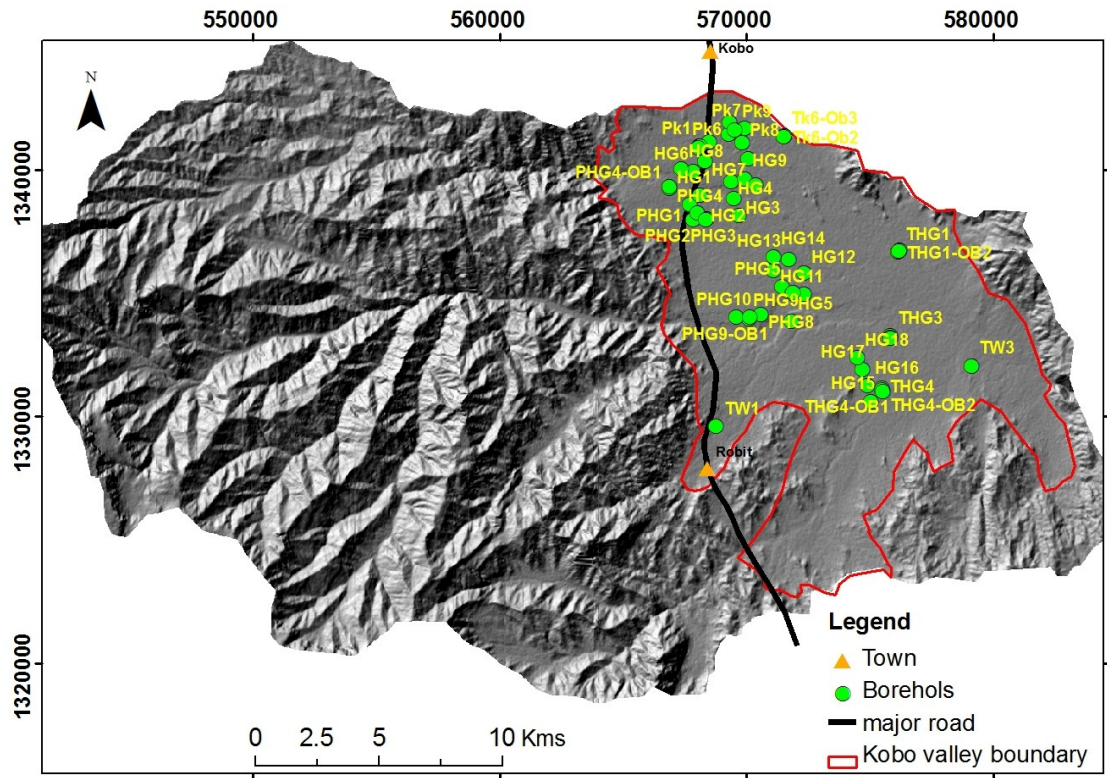


Figure 5.15: Location map of boreholes used for pumping test analysis

In a pumping test, the type of aquifer and the inner and outer boundary conditions dominate at different times during the test. They affect the drawdown behavior of the system in their own individual ways. So, to identify an aquifer system, one must compare its drawdown behavior with that of the various theoretical models (Kruseman and Ridder 1994). The model that compares best with the real system is then selected for the calculation of the hydraulic characteristics. Construction of diagnostic plots (log – log) and specialized plot (semi – log) enables to identify the aquifer system of the area. The characteristic shapes of the curves can help in selecting the appropriate model (Kruseman *et al.* 1994).

The last method which is not more commonly used method but give strength for the above methods is observing the static water level/piezometric or potentiometric surface of the well.

In confined aquifer, the piezometric surface will lie above the top of the aquifer while in unconfined aquifer the static water level (SWL) doesn't lie above the top of the aquifer.

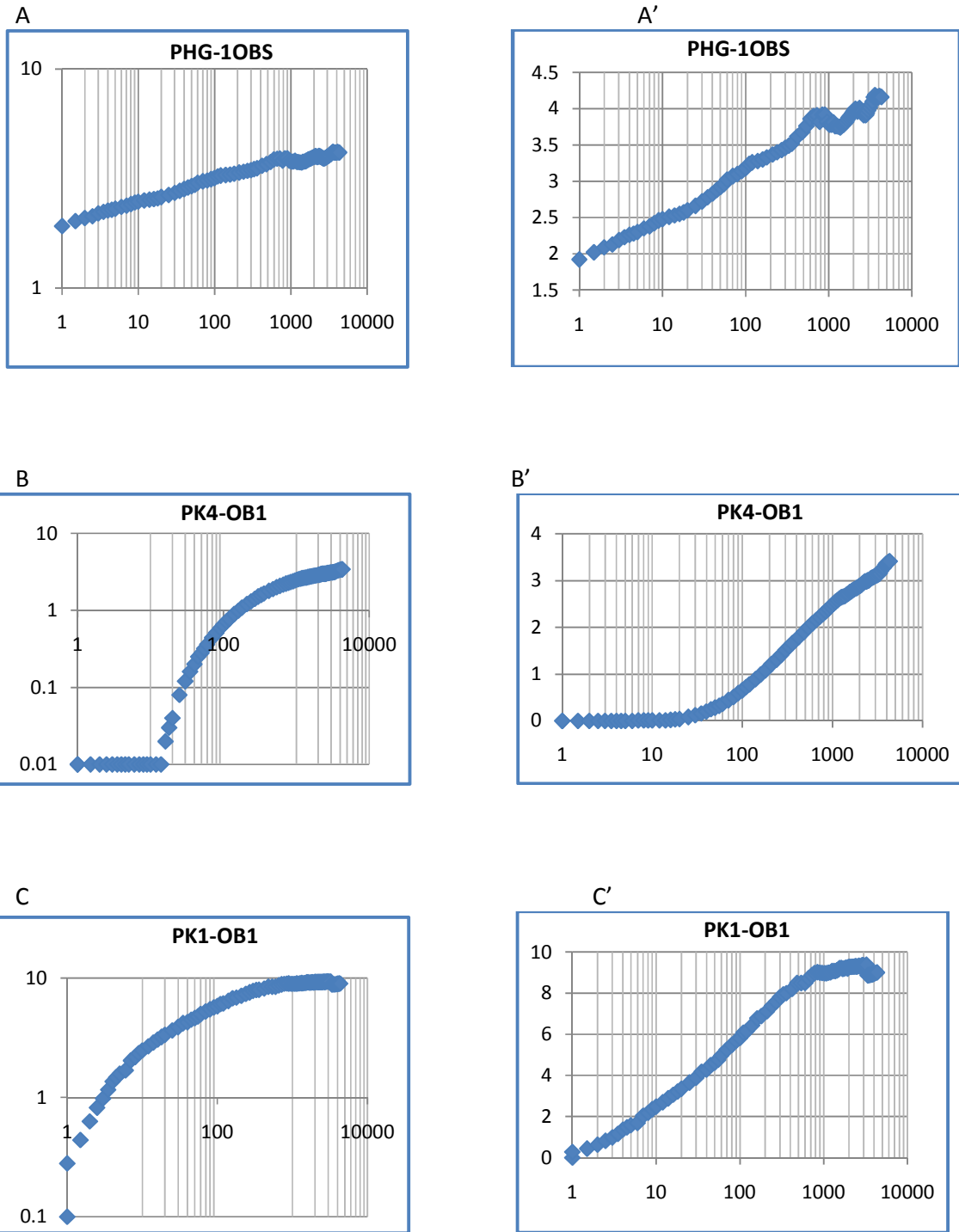


Figure 5.16: A, B and C are diagnostic plots and A', B' and C' are specialized plots
Based on the analysis discussed above, PHG3, PHG9, THG3, THG4, PK4, PK7, PK8, TK7, HG12, and HG13 wells are treated to be confined aquifers because most of them

have showed a best fit with Theis type curve and the lithological logs of these wells is dominated with inter layered clay beds between sand, gravel, pebble, cobble, boulder and mixture of these, PK1 and PK2 are leaky and all the remains are unconfined aquifer.

5.5.3. ESTIMATION OF HYDRAULIC PARAMETERS

The well logs and the geophysical logs used to determine the type of aquifer. The shape of the graph of the pumping test data on a double logarithmic and semi-logarithmic plot was used as a confirmation of the earlier anticipated aquifer type (See figure 5.16). For the aquifer parameter calculation basically the three techniques have been used; for confined aquifers the Theis method, for semi (un) confined aquifers Hantush and for the unconfined aquifers the Neuman method is employed. Whereas for the case of recovery test; Theis recovery method is used. All the mentioned methods are manipulated by using aquifer test software known as Aquitest 3.5. The analysis result of pumping test data is presented in appendix 1. Note that aquifer thickness is assumed as the total length of the screened interval in the well for the calculation of hydraulic parameters.

5.5.3.1. TRANSMISSIVITY (*TD* or *T*)

It is the product of the average hydraulic conductivity K and the saturated thickness of the aquifer (D). It is the rate of flow under a unit hydraulic gradient through a cross – section of unit width over the whole saturated thickness of the aquifer (Kruseman and Ridder. 1994).

The results of the pumping test interpretations in the wells have been used to prepare a transmissivity map for the Alluvial Aquifers in the study area (see figure 5.17).

The wells tapping the Interfluvial, Fan Foot Plains deposits, and the Central Valley Flood Plain Quaternary deposits, have the lowest values for the transmissivity ($<250 \text{ m}^2/\text{d}$), whereas the wells tapping the colluvial deposits and the Quaternary alluvial deposits in the western part of the area at the foot of the mountains shows the highest transmissivity values (up to $4320 \text{ m}^2/\text{d}$). This is explained by the geological composition of the rocks in these areas. In the west along the escarpment boundary, the geological material mainly consists of coarse sand, gravel, pebbles and boulders. This correlates with the higher transmissivity. The transmissivity value resulted from pumping test data analysis is presented in appendix 1. The transmissivity value ranges from $6.85 - 4510 \text{ m}^2/\text{d}$ and the mean, and median are $492.38 \text{ m}^2/\text{d}$, and $199 \text{ m}^2/\text{d}$ respectively.

For the purpose of qualitative analysis the transmissivity values of the wells can be categorized into five groups as follows.

- very low: $<100\text{m}^2/\text{d}$
- low : $100\text{m}^2/\text{d}$ to $250\text{m}^2/\text{d}$
- medium: $250\text{m}^2/\text{d}$ to $500\text{m}^2/\text{d}$
- high : $500\text{m}^2/\text{d}$ to $1000\text{m}^2/\text{d}$
- very high: $>1000\text{m}^2/\text{d}$

Aquifers with transmissivity greater than $149.2\text{m}^2/\text{d}$ can be sustain irrigation development (Johnson, 1966, as cited Sileshi Mamo, 2007).

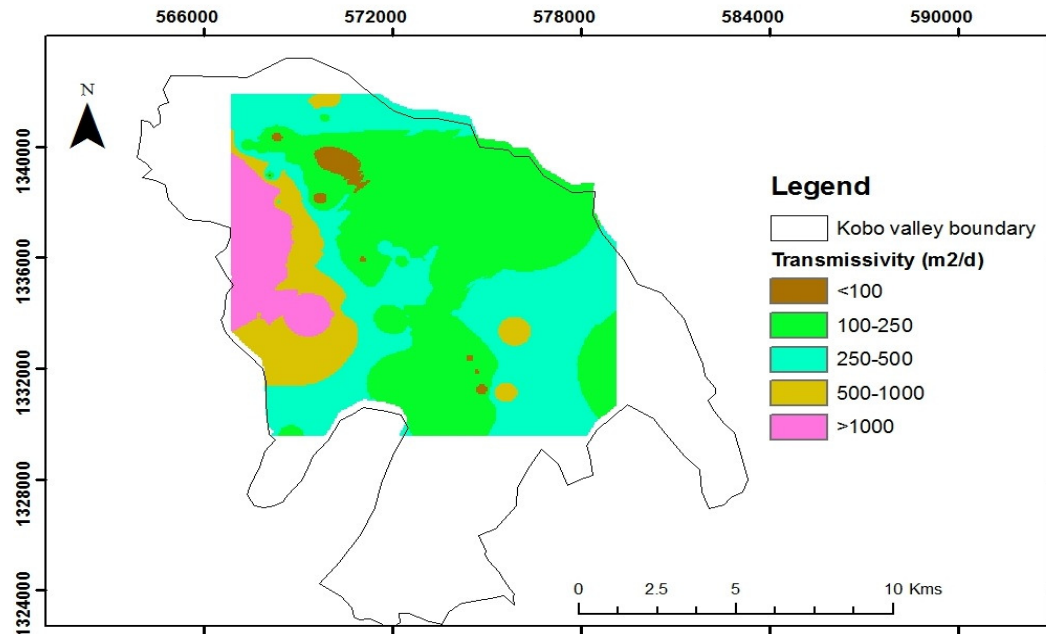


Figure 5.17: Spatial distribution of Transmissivity value map of the valley (in m^2/d)

5.5.3.2. *HYDRAULIC CONDUCTIVITY (K)*

Hydraulic conductivity is the volume of water that will move through a porous medium in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow (Kruseman and Ridder 1994). It determines the ease by which water can move through aquifers. It therefore, determines the productivity of the aquifer.

Hydraulic conductivity is high in the western side of the graben than the central and eastern side of catchment. The hydraulic conductivity value resulted from pumping test data analysis is presented in appendix 1. The hydraulic conductivity value ranges from 0.19 – 125 m/d and the mean, and median are 10.9 m/d, and 4.25m/d, respectively.

For the purpose of qualitative analysis the transmissivity values of the wells can be categorized into different groups as follows.

- Low: $<5\text{m}/\text{d}$
- Medium: $5\text{-}10\text{m}/\text{d}$

- High: 10-20 m/d
- Very high: >20 m/d

There are few boreholes that tap the volcanic aquifer within the studied basin. The only data that was obtained from the boreholes is drilled depth which is relatively shallow, depth to water level and discharge. Therefore, it was difficult to calculate the hydraulic parameters for the volcanic aquifer. Therefore, this fracture aquifer is believed to have generally moderate permeability and low productivity, with limited water supply to communities mainly by developing springs (Sileshi Mamo, 2007).

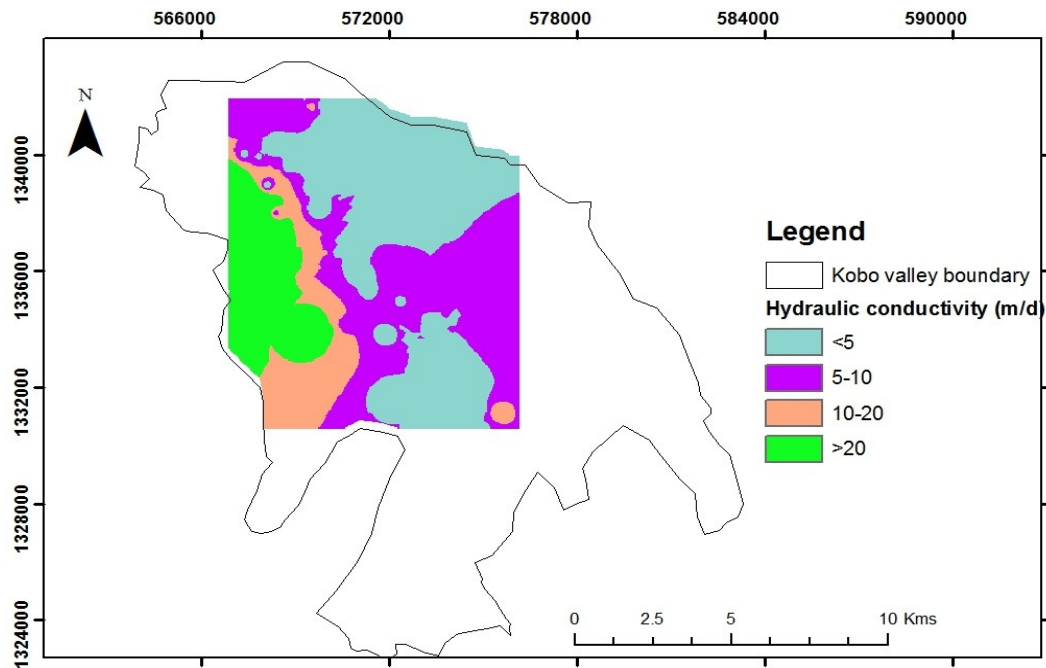


Figure 5.18: Spatial distribution of Hydraulic conductivity value map of the valley (in m/d)

5.5.3.3. SPECIFIC CAPACITY

The specific capacity of a well is the yield per unit drawdown, and is determined by dividing the pumping rate at any time by the drawdown at the same time. The specific capacity of a well depends both on the hydraulic characteristics of the aquifer and on the construction, pumping rate, and other features of the well.

The data used for the calculation of specific capacity are obtained from constant rate pumping test i.e. from the constant discharge rate used in the constant rate test and the pseudo steady state drawdown obtained at the end of constant rate test.

Values of specific capacity, available from pumping wells for which aquifer-test data are not available, are widely used to estimate transmissivity (U.S. Army Corps of Engineers, 1999).

There is a close relationship between the recorded specific capacity and transmissivity values, based on data from 36 wells. The best fit regression equation through the data pairs is $T = 0.529Sc + 157.7$ with a goodness of fit ($R^2 = 0.79$) (Figure 5.19a).

Log transformation is applied to the data to improve the normality of the data, to stabilize the variance, to transform the data from skewed to symmetric distribution and there by improve the goodness of fit (R^2) value.

For this analysis 36 pairs of log transformed values of specific capacity and transmissivity data are plotted against each other and fit a least squares regression line through them. Therefore log transmissivity can be directly estimated from the best fit regression equation. The best fit regression equation through the data pairs is $T = 1.200Sc - 0.711$ with a goodness of fit ($R^2 = 0.82$) (Fig 5.19b) using linear relationship between log transformed values of both parameters.

The specific capacity is calculated for 36 wells which are in different aquifer settings and having variation in discharge rates (Appendix 2).

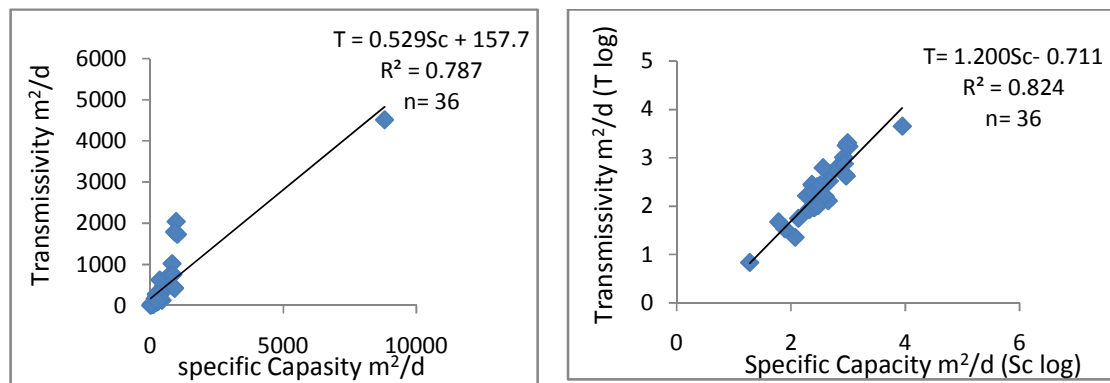


Figure 5.19: a. Empirical relation between transmissivity and specific capacity with linear relationship. b. Empirical relation between log transformed transmissivity and log transformed specific capacity with linear relationship.

5.6. GROUNDWATER POTENTIAL EVALUATION

5.6.1. GROUNDWATER RECHARGE ESTIMATION

The amount of water that may be extracted from an aquifer without causing depletion is primarily dependent upon groundwater recharge. Thus, a quantitative evaluation of the spatial and temporal distribution of groundwater recharge is a prerequisite for operating a groundwater resources system in an optimal manner.

When estimating groundwater recharge it is essential to proceed from a good conceptualization of different recharge mechanisms and their importance in the study area.

Besides this conceptualization the objectives of the study, available data and resources, and possibilities of obtaining supplementary data should guide the choice of recharge estimation methods (Sophocleous, 2004).

A number of methodologies are used to estimate recharge. These can be classified as:

- Direct or indirect;
- Physical, chemical, or isotopic;
- Methods based on the analysis of inflow, outflow, or aquifer response;
- Methods based on the unsaturated or saturated zones; and
- Methods based on numerical modeling of groundwater flow, soil-water flow, both soil and groundwater flows, or modeling of the hydrologic balance at plot, field, or watershed scales.

Here we combine these methodologies into two groups: *physical methods* and *tracer methods*.

In arid and semiarid areas, where deep drainage fluxes are low and water tables are deep, interpreting groundwater hydrographs and water table rises may be misleading for estimating rates of groundwater recharge; chemical and isotopic methods are likely to be more successful than physical methods in such cases (Sophocleous, 2004). Major source of recharge to the aquifer of the basin fill sediments underlying the plane are rainfall and infiltration from streams and from floods that occur during high rainfall in the highlands. Lateral flow from mountainous terrain which is likely, significant has not been considered for the lack of quantitative data. Three common methods are employed to estimate the annual groundwater recharge capacity of the Kobo valley based on availability of data. Although each method has its own limitation, the three methods in combination will give the order of magnitude of the recharge capacity of the valley. The result of each method will be discussed hereunder.

5.6.1.1. CHLORIDE MASS BALANCE METHOD

The chloride ion is used in groundwater recharge studies because of its conservative nature. The ion neither leaches from nor is absorbed by the sediment particles, and it does not participate in any chemical reaction. Schoeller (1941) was the first who draws attention to chloride in the water cycle for determining groundwater recharge.

The assumptions in the CMB approach for recharge calculations are that:

1. There is no Cl^- source in groundwater storage prior to the rainfall.

2. There are no additional sources or sinks for Cl⁻ concentration in the area of application.
3. The rainfall either evaporates or infiltrates in the region without any runoff, which is a rather unrealistic assumption and can only be valid for low-intensity rainfall events. However, most often, rainfalls are intense, especially at the highland portions of the study area, due to orographic conditions.
4. Long-term rainfall and its Cl⁻ concentration amounts have a balanced situation, i.e. they are in a steady-state condition. This implies stable and long-term averages, as the classical CMB method requires.

On the basis of these assumptions, the fundamental equation applicable to recharge calculations is presented by Wood and Sanford (1995) as

$$R_{gw} = \frac{P \cdot Cl_p}{Cl_{gw}} + D \quad \dots \text{equation 1}$$

where, R_{gw} = groundwater recharge (Mm³/y)
 P = average annual precipitation (Mm³/y)
 $(P_{\text{effective}} = \text{Precipitation} - \text{surface runoff})$
 Cl_p = chloride content in precipitation (mg/l)
 Cl_{gw} = harmonic mean of chloride concentration in groundwater (mg/l)
 D = dry deposition of chloride measured during the dry season (mg/l)

The chloride concentration in groundwater may originate from different flow components in the unsaturated Zone. Hence, the calculation of groundwater recharge rate using chloride concentrations of groundwater results in total recharge rate. In this study area CMB was done for western mountain and the valley and escarpment separately.

Forty one groundwater samples were analyzed for their chloride content. The chloride content of the collected groundwater samples ranges from 6.18 to 92mg/l with a standard deviation 21.38. The recharge calculation by CMB method gives an average long-term estimate of recharge. According to Eriksson (1985), the average groundwater chloride content should be calculated as the harmonic mean, given by equation 2.

$$Cl_{gw,avg} = \frac{N}{\sum_{i=1}^N \frac{1}{Cl_{gw}}} \quad \dots \text{equation 2}$$

Where:

Cl_{gw} = individual chloride concentration of samples

$Cl_{gw.avg}$ = harmonic mean of the chloride content in the groundwater

N = total number of observations.

Based on the collected groundwater samples, the harmonic mean of the chloride content in the groundwater of Kobo valley area was calculated as 18.20mg/l. (appendix 4).

The chloride content of water from the mountain was estimated from the water sample of springs emerging from the highlands and water sample from the rivers. Accordingly the harmonic mean of the chloride content of the highland area was resulted as 13.7mg/l. (appendix 4). However, in this study there is no record in relation to dry chloride deposition (D) on the study area. Therefore, it is assumed to be Zero. Hence the equation 1 was reduced to:

$$R_{gw} = \frac{P_{eff} Cl_p}{Cl_{gw}} \dots\dots Equation 3$$

Therefore, Cl_p for valley and escarpment = 3.01mg/l

Cl_p for western mountain = 0.68mg/l

The groundwater recharge for Kobo valley/escarpment and western mountainous area using CMB method was estimated as 13.1Mm³/y and 16.9Mm³/y, respectively. The total groundwater recharge with the catchment is 30Mm³/y. This calculation is based on the assumption that all recharge water from the plateau and escarpment flows and stored within the graben/valleys floor.

5.6.1.2. GROUNDWATER FLOW/DARCY APPROACH

Groundwater Flow/Darcy Approach: The product of transmissivity (m²/year) of the aquifer, the gradient (i) of groundwater table and the estimated flow channel width (m) for the aquifer gives the annual recharge of groundwater. The knowledge of the spatial distribution, homogeneity/heterogeneity of the aquifer and the slope of the groundwater table are critically important in the application of this method.

This approach considers groundwater flux through a flow width perpendicular to the general gradient of groundwater flow. The annual discharge of this groundwater can be estimated using the following formula;

$$\text{GWR} = 365 \times T \times I \times B$$

Where, GWR = groundwater recharge (m^3/year)

T = transmissivity (m^2/d)

I = hydraulic gradient (dh/dl)

B = Width of flow at right angle to the direction of flows (m)

365 = number of days in a year

The gradient of the main groundwater flow for Kobo valley is 0.012. Average transmissivity value is equals to $492\text{m}^2/\text{d}$ (from section 6.4.3.1) and the flow width (Kobo to Robit plain) is approximated as 14000m.

Inserting the specific values into the above formula, gives the annual flow of groundwater is to be $30.2 \times 10^6 \text{m}^3/\text{year}$ or 30.2MCM.

5.6.1.3. WATER BALANCE APPROACH

Water balance represents the hydrological gains and losses of a given system (reservoirs, column of soil, aquifer, river basin, etc) over a specific period of time. Quantification of the rate of natural groundwater recharge is a basic pre-requisite for efficient groundwater resource management. Water balance models were developed by Thornthwaite (1948) and revised by Thornthwaite and Mather (1955). The method is essential procedure, which estimates the balance between the inflow and outflow of water. Generally, water balance has the following form:

Inflow = outflow \pm change in storage

This could be rewriting for the calculation of groundwater recharge as follow

Groundwater recharge = (precipitation + surface water inflow + imported water + Groundwater inflow) – (Evapotranspiration + reservoir evaporation + surface water out flow + exported water + Groundwater outflow + withdrawal) \pm Change in storage (Fetter, 2001).

The main purpose of this computation is to make a quantitative evaluation of the amount of water that percolates in to the ground to recharge the groundwater circulation occurring in

the investigating area. Therefore, assumption made to derive the water balance equation for the study area, are summarized as follows:

- a) Since the computation is made annually, net change of the soil moisture and groundwater storage is assumed to be zero.
- b) The area is part of the regional groundwater flow system and groundwater is not in closed system. Therefore, groundwater inflow from adjacent basin or area is equal to groundwater outflow in the adjacent basin or area.

For a long term calculation on annual bases the above equation could be rewritten as follows:

Infiltration (recharge) = (Precipitation – Actual Evapotranspiration – surface outflow – Withdrawal)

The annual basin precipitation as calculated using isohythal method is found to be 871.53mm the total area of the basin is 806km² (702.45MCM).

The annual actual evapotranspiration for the basin computing from Turc method is found to be 655mm (527.9MCM).

The annual surface outflow is approximated to be 98.4MCM.

The population living within the project area and getting a water supply from wells is 221894. Assuming that 25 l/day is the consumption per person taking all other factors in to account, the total amount being abstracted can be estimated as follow:

$$Q = \text{Num } R$$

Where: Q - total extraction per year

Num – size of population

R – Rate: 25 l/day/person

$$\begin{aligned} Q &= 221894 \text{ person} * 25 \text{ l/day/person} * 365 \text{ days} \\ &= 2024782750 \text{ l/year (} \\ &= 2 \text{MCM} \end{aligned}$$

Accordingly the annual recharge of ground water in the aquifer of the study area estimated from the above equation is:

$$R = 702.45\text{MCM} - 527.9\text{MCM} - 98.4\text{MCM} - 2\text{MCM}$$

Accordingly the amount of potential groundwater recharge available on the study area is about 74.15MCM. If the above assumptions are true then this much amount of water could be abstracted from the entire basin annually without affecting the ground water table.

The recharge estimation by CMB, Darcy and water balance methods is **30MCM/year, 30.2 MCM/year and 74.15 MCM/year**, respectively and average value of **44.8MCM/year**.

5.6.2. GROUNDWATER RESERVE ESTIMATION IN KOBO VALLEY

An estimate of ground water reserve is desirable for planning the optimum utilization for future development of the ground water resources of an area. The total subsurface water reserve is a function of saturated thickness and storage coefficient/specific yield. The aquifer system is generalized into water table aquifer of the sediment.

The groundwater reserve in the basin fill could be estimated using a relation:

$$V = S_y * A * b$$

Where V: reserve (m^3)

S_y: specific yield

A: surface area of the valley plain (m^2)

b: saturated thickness (m)

The specific yield for Kobo valley is 0.1, surface area of the valley estimated as 175Mm² and an average saturated thickness of 116m. Therefore, groundwater reserve of the valley is estimated as 2033MCM.

CHAPTER SIX

HYDROCHEMISTRY

6. GENERAL

Natural water consists of dissolved minerals, dissolved oxygen, suspended particulate materials and etc. the chemical composition of natural water is derived from different sources of solutes including gases from the atmosphere, weathering and erosion of rock and soil, solution or precipitation, reactions occurring below the land surface and effect resulting from human activities (Hem, 1985). The chemistry of groundwater in the saturated zone is controlled by chemical reaction rate, residence time within the saturated zone, and mineralogy of the rock matrix, where residence time and flow path are determined by factors such as aquifer thickness, permeability and amount of recharge (Griffioen, 2004). These factors combine to different degrees to create diverse water types with compositions that vary with space and time. The objectives of the hydrochemical investigations are to determine the sources, concentration, and fate of dissolved constituents within the physical framework of flow and transport (Griffioen, 2004). The approach divides the water samples into hydrochemical facies (water types), which are groups of samples with similar chemical characteristics that can then be correlated with location.

The analytical results were presented spatially to allow visualization of the water types and their relationships. In order to understand the groundwater flow system and interaction among waters of different provenance, hydrochemical distribution maps of different parameters have also been prepared. The various types of display and discussion on the hydrochemistry of the study area are presented as follow:

6.1. EVALUATION OF HYDROCHEMICAL PARAMETERS

6.1.1. PHYSIOCHEMICAL PARAMETERS

6.1.1.1. PH

The PH value ranges from 6.96 to 8.48 and has a mean and median are 7.66 and 7.65 respectively indicating that it has a normal distribution. All tested samples have PH greater than 7.0 except 005SP. Hand dug wells (51), springs (58, HGSP1) and borehole (TW2) and boreholes located on the eastern and central part of the valley are displayed PH values closer to 8. Whereas springs located on the recharge area are display relatively lower PH values closer to 7. Therefore, the ground water of the valley is considered to be alkaline.

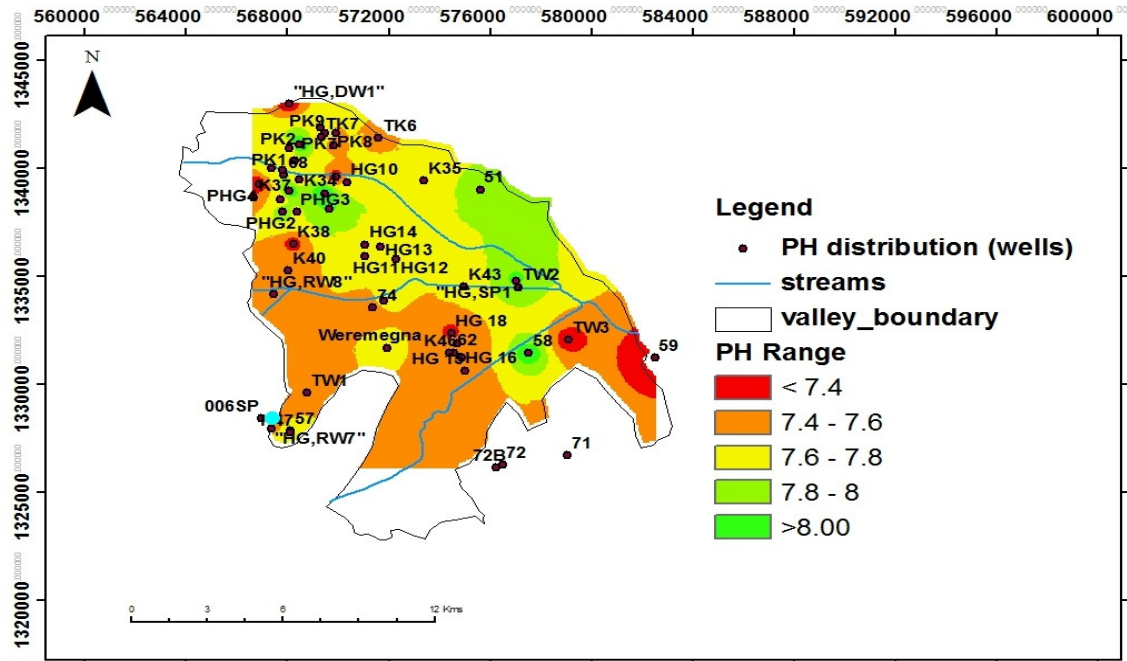


Figure 6.1: Spatial variation of PH value within the valley

6.1.1.2. ELECTRICAL CONDUCTIVITY (EC)

Electrical conductivity is the ability of a substance to conduct electric current (Hem, 1985). The presences of charged ionic species in water make it conductive. In other words, EC is a measure of the total concentration of ion. Conductance is expressed as micro Siemens, and is used as an indirect measure of TDS (mg/l).

The conductivity of the groundwater in the area ranges from 330 mS/cm in (HG,RW8) to 1584 mS/cm in a hand dug well (51). When we consider only the boreholes, the conductivity ranges from 430 mS/cm to 1325 mS/cm in (K35). Higher conductivities are observed in wells located in the eastern and north eastern of the valley floor which compared to those located at the western escarpment. This increase in conductivity towards the axis of the valley could be associated with the geology, the ground water flow direction and possible evaporation. The groundwater was found to flow from the western escarpment towards the valley floor (see Chapter 5). Generally, dissolved solid concentrations in groundwater increase along flow paths, from the surface to the saturated zone and through the aquifer, due to the dissolution of minerals (Freeze and Cherry, 1979).

The water quality results show that electrical conductivity (EC) and total dissolved solid (TDS) have a good correlation of $TDS = 0.85EC - 121.2$ with $R^2 = 0.835$ (figure 6.3).

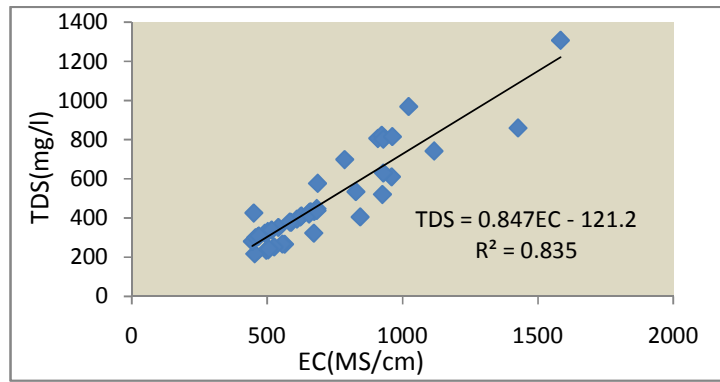


Figure 6.3: TDS – EC correlation for the water sample

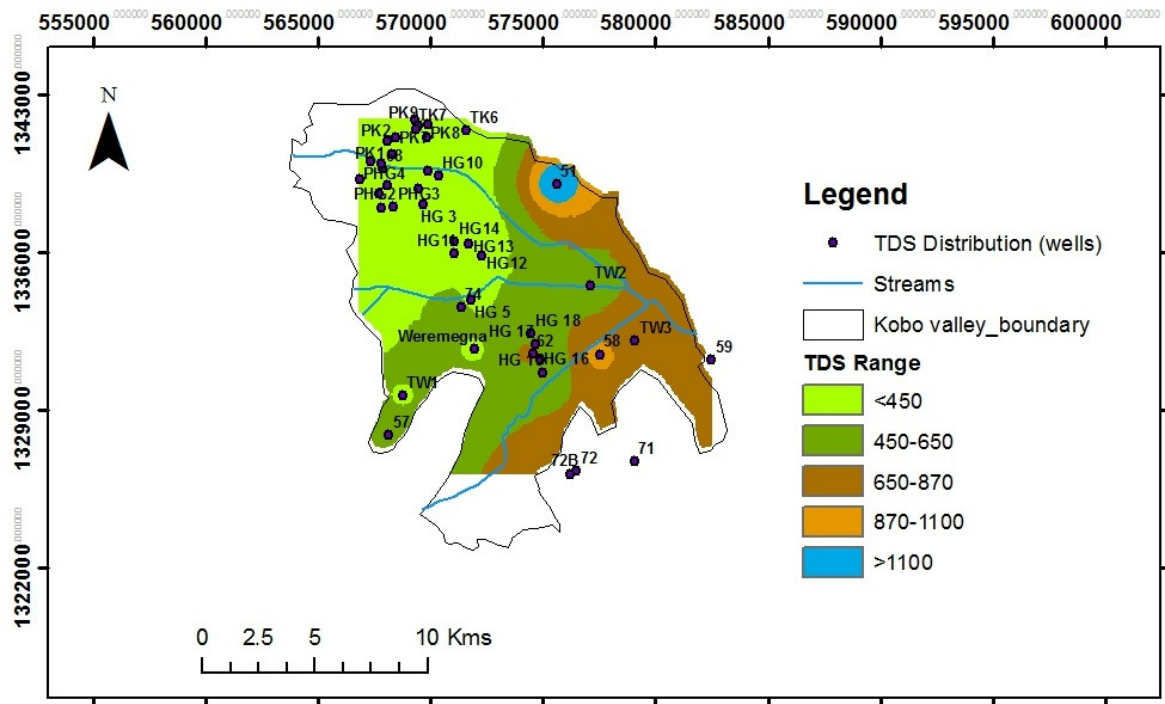


Figure 6.4: TDS map of the Kobo valley

6.1.1.4. HARDNESS

Hardness of water is defined as its content of metallic ions which reacts with sodium soaps to produce solid soaps or scummy residue and which react with negative ions, when the water is evaporated in boilers, to produce solid boiler scale (Camp, 1963). It is predominantly caused by divalent cations such as calcium, magnesium, alkaline earth metal such as iron, manganese, strontium, etc. It is a water quality indication of the concentration of alkaline salts in water, mainly calcium and magnesium. Hardness is normally expressed as the total concentration of Ca^{2+} and Mg^{2+} as milligrams per liter equivalent $CaCO_3$. The total hardness is defined as the sum of calcium and magnesium concentrations, both

expressed as CaCO₃ in mg/l. It can be determined by substituting the concentration of Ca²⁺ and Mg²⁺, expressed in milligrams per liter, in the expression

$$\text{Total Hardness} = 2.5 (\text{Ca}^{2+}) + 4.1 (\text{Mg}^{2+})$$

Table 6.1: Total hardness of water sample collected from study area.

Sample ID	Total Hardness (CaCO ₃) mg/l	Sample ID	Total Hardness (CaCO ₃) mg/l
58	363.0	K35	342.1
59	116.0	K37	186.9
71	383.6	K38	228.4
72	410.4	K40	157.2
72B	428.2	K43	242.6
74	318.6	K46	328.3
57	270.5	K47	242.4
62	356.8	PHG1	217.5
51	443.5	PHG2	260.0
HG 7	240.2	PHG3	222.3
HG 8	220.4	PHG4	173.8
HG9	404.2	PK1	251.5
HG10	306.8	PK2	253.4
HG11	255.232	PK6	326.9
HG12	257.319	PK7	314.4
HG13	290.74	PK8	282.9
HG14	290.72	PK9	324.7
HG 15	348.078	TK6	161.3
HG 16	501.385	TK7	326.9
HG 17	507.29	WeremegnaBH	298.9
HG 18	399.95	Kelkeli river	141.8
K34	185.0		

According to Sawyer and McCarty (1967) Hardness classification of water (mg/l) given by:-
 Hardness range CaCO₃ (mg/l)
 0 to 75 soft
 75 to 150 Medium hard
 150 to 300 Hard
 >300 Very hard

As can be seen from table 6.1 most water samples fall in the range of hard to very hard except spring (59) and Kelkeli River which are moderately hard. That high hardness is credited to the geological formations that characterize the area which are composed of Quaternary sediments which are derived from Tertiary basalt. The dominant cations of the basin are calcium and magnesium.

6.2. WATER SAMPLING AND ACCURACY OF CHEMICAL ANALYSIS

Groundwater samples were collected from springs and boreholes during the field visit in august 2010. Beside this existing groundwater samples analysis results were collected and used in this study. A total of 6 new samples which were collected and analyzed during field work and 67 existing chemical analysis results were acquired from different offices and literature. The location of the water samples are indicated in figure 6.5 most of the samples were taken from the valley part of the catchment and only six samples were taken from the highland and escarpment. This is because of the borehole distribution of the basin. The chemical analysis of the sample collected during the field visit was conducted by JIJE LABOGLASS P.L.C laboratory service. Electrical conductivity and PH were measured with portable devices during the field investigations. The details of the water samples are presented in Appendix 6.

6.2.1. RELIABILITY CHECK

To evaluate the accuracy of the chemical analysis results two method were used. First the balance between Cations and Anions measured by the Electro Neutrality (eq. 4). Based on the electro-neutrality, analysis of water samples with a percent balance error <5% is regarded as acceptable (Fetter, 2001). To evaluate the accuracy of the chemical analysis, a reliability check was conducted using AquaChem software. 35 samples have shown a value of less than 5 and 3 samples a value between 5 and 8. These are HG8, 59, and 62.

$$\text{Electro-neutrality} = \frac{(\text{sum cations} - \text{sum anions})}{(\text{sum cations} + \text{sum anions})} * 100 \dots\dots \text{equation 4}$$

Second technique used to check accuracy of chemical analysis is to compare calculated conductivity with measured EC with the following relationship (eq. 5) (Appelo et.al, 1996).

$$\sum \text{anions}(\text{meq/l}) = \sum \text{cations}(\text{meq/l}) = \text{EC}/100(\mu\text{s/cm}) \dots\dots \text{equation 5}$$

Accordingly the above calculation was made for all the samples and the result is tabulated on Appendix 5. The table shows a more or less good relationship between anions and EC/100.

Generally, out of 67 samples 54 samples have both major cations and anions measurements. 13 samples lack the measurement of Na+, and K+ and 11 samples have electrical neutrality of greater than five that rejected form analysis.

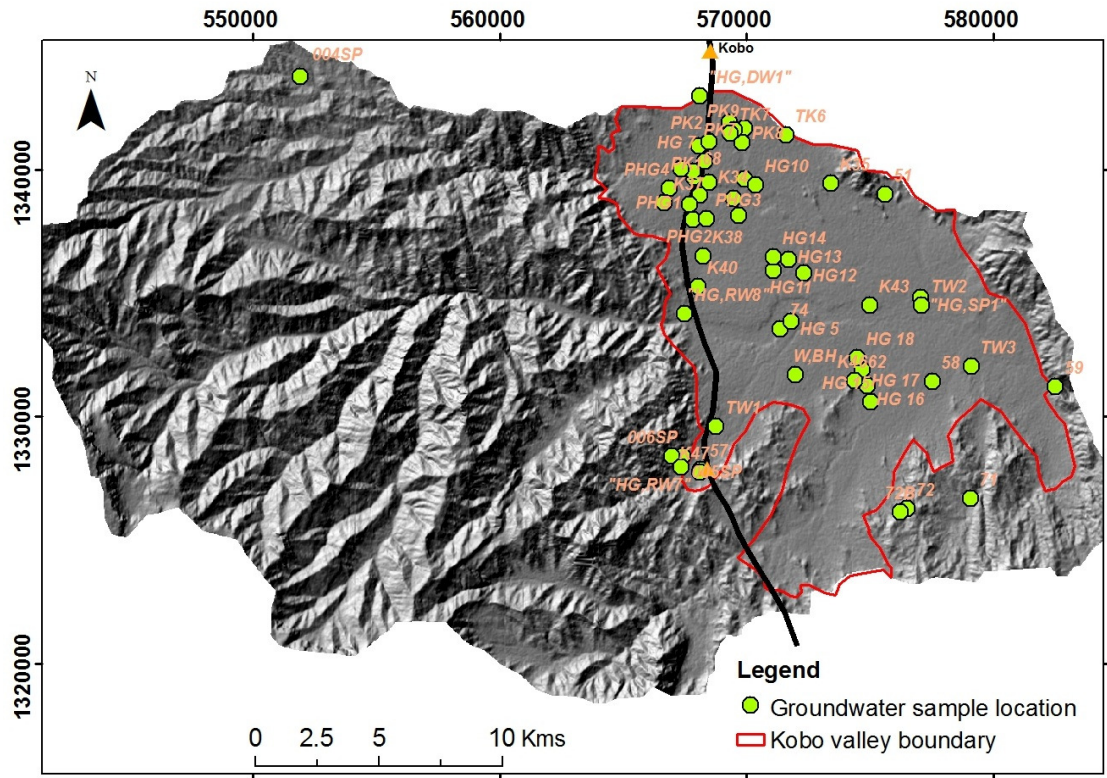


Figure 6.5: Location of hydrochemical sampling points in the study area

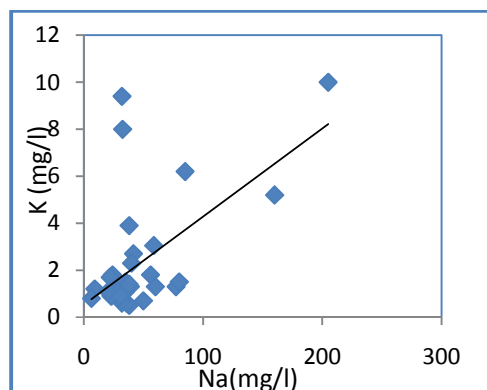
6.3. MAJOR IONS

6.3.1. SODIUM AND POTASSIUM

Sodium is the second most abundant cation next to calcium in the basin (Table 6.2). In the samples examined it ranges from 6.4mg/l in HG8 to 205mg/l in spring (59). The mean is about 44mg/l. Most of the samples show values ranging from 20 to 60mg/l.

Na⁺ concentration shows in general an increasing tendency from the west escarpment towards the eastern tip of the study area (figure 6.12). This is because of long time of water-rock interactions. The main source of sodium in the study area could be sodium plagioclase (albite) and to some extent sodium may be retained by adsorption on mineral surface of lacustrine deposits having high cation exchange capacities such as clay before directly recharge to groundwater.

Potassium is lower than sodium because it is resistant to chemical attack and species containing sodium and calcium are more susceptible to weathering. The low concentration of potassium in general could be attributed to the lesser proportion of potassium feldspar.



6.3.2. MAGNESIUM AND CALCIUM

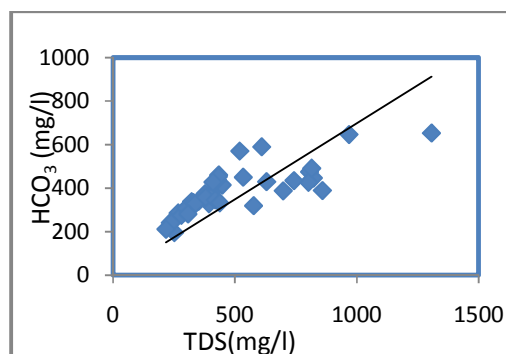
Calcium is the most abundant cations followed by sodium and magnesium in the study area as per concentrations in milligram per liter. Because of their similar geochemical behavior calcium and magnesium are treated together. Most of the samples in the study area are calcium and magnesium bicarbonate water types. Calcium ranges from 30 mg/l in spring (59) to 168 mg/l in HG16. Higher concentrations are found at the centre and south west of the valley. Magnesium ranges from 7.3mg/l in TW1 to 57.12 in HG9. Most of the samples show values ranging from 20 to 50mg/l. the main source of Calcium in the study area could be derived from weathering of calcic plagioclase and calcium rich pyroxene.

6.3.3. CARBONATES

Carbonate in the area is mainly in the form of bicarbonate. Bicarbonate is the major ion in the groundwater and the river water. The concentration of bicarbonate in boreholes ranges from 196 mg/l in HG5 to 590 mg/l in HG17. The highest bicarbonate concentrations were detected in hand dug wells which have more than 650 mg/l of bicarbonate.

The mean concentration for the boreholes is about 362 mg/l. Bicarbonate is by far the largest anion in the study area. All samples that show higher TDS with high concentration of HCO_3^- and the lower TDS is the vice verse.

The chemical weathering of Aluminium-silicate like Albite or K-feldspar controls the CO_2 content of water therefore it's PH (Langmuir,1997). Higher concentrations of HCO_3^- are observed in wells located in the central plain and a kind of decrease to the eastern and western tip of the valley can be noted.



6.3.4. SULPHATE AND NITRATES

Sulphate is the second most abundant anion next to bicarbonate in the region. In the boreholes examined it ranges from 0.29 mg/l in PHG3 to 119 mg/l in HG18. The mean is about 27 mg/l. Most of the samples are between 1.5 mg/l and 30 mg/l. Like other major ions the highest concentration is found at the centre and east of the valley.

The mean concentration of nitrate is found to be 15.7 mg/l in the region. It ranges in the boreholes from 0.2 mg/l in HG14 to 7.5 mg/l in HG5. The highest nitrate concentrations were detected in the hand dug wells and springs which are more than 30mg/l. High concentration of nitrate in some springs entail a local source that could possibly be associated with agricultural chemicals and also human and animal wastes particularly on the hand dug wells. The relative lower concentration of Nitrate in boreholes is related to the absence of deep aquifers affected by anthropologic source related to agricultural fertilizers and animal manures.

6.3.5. CHLORIDE

Chloride is a conservative tracer that has frequently been applied in flow path tracking and recharge estimation. The mean concentration of chloride is 27 mg/l. In the boreholes it ranges from 0.5 mg/l in HG3 to 92.3 mg/l in TW3. Most of the samples are between 5.5 mg/l and 50 mg/l. The chloride concentration increases from west to east as the general groundwater flow Direction.

Table 6.2: Summery statistics of the groundwater sample result

Summary statistics of the groundwater sample result					
Constituent	Unit	Minimum	Maximum	Mean	Median
EC	µS/cm	314	1584	679.7031	614.5
TDS	mg/l	217	1306.7	480.5044	410
PH		6.96	8.48	7.66462	7.65
Ca ⁺²	mg/l	30	168	69.90795	59.64
Mg ⁺²	mg/l	7.3	57.12	31.33154	31.6
Na ⁺	mg/l	6.38	205	43.91974	32
K ⁺	mg/l	0.5	10	2.173077	1.3
HCO ₃ ⁻	mg/l	196	654	387.2572	374.66
NO ₃ ⁻	mg/l	0.04	84.17	15.71269	3.3
Cl ⁻	mg/l	0.5	92.3	26.95974	19.86
F ⁻	mg/l	0	1.08	0.39363	0.35
SO ₄ ²⁻	mg/l	0.29	221	27.18256	12.3
SAR		0.146	8.28	1.202914	0.84

6.4. CLUSTER ANALYSIS

Statistical techniques, such as cluster analysis, can provide a powerful tool for analyzing water-chemistry data. These methods can be used to test water quality data and determine if samples can be grouped into distinct populations (hydrochemical groups) that may be significant in the geologic context, as well as from a statistical point of view. The ability of cluster analysis to classify groundwater chemistry into coherent groups that may be distinguished in terms of aquifer type, subsurface residence time, and degree of human impact on water chemistry provides a good opportunity to understand groundwater geochemical evolution among the different groups or subgroups (Seifu Kebede, 2004).

In this research work, hierarchical cluster analysis (HCA) was used to classify the samples into distinct hydrochemical groups based on their similarity.

Comparisons based on multiple parameters from different samples are made and the samples grouped according to their “similarity” to each other. The classification of samples according to their parameters is termed Q-mode classification. This approach is commonly applied to water- chemistry investigations in order to define groups of samples that have similar chemical and physical characteristics because rarely is a single parameter sufficient to distinguish between different water types (Cüneyt et al., 2002). The HCA is designed to group water samples using Euclidean distance (straight line distance between two points in n-dimensional space defined by n variables) as similarity measurement, together with Ward’s method for linkage, produced the most distinctive groups where each member within the group is more similar to its fellow members than to any member from outside the group (Cüneyt et al., 2002). A Microsoft *EXCEL* add-in module *XLSTAT 7.5* was used to conduct the HCA for water samples from previous and present studies. The Euclidian distance between Na^+ , K^+ , Mg^{+2} , Ca^{+2} , Cl^- , SO_4^{-2} , HCO_3^- , PH and EC values were used to calculate similarity among samples with Ward’s method for linkage. The raw chemical data were log transformed and standardized so that variables had equal weight.

Using HCA classification method the collected water samples are categorized into four distinct classes that clearly correlate with the geological and hydrogeological set up of the area. Each cluster group is plotted on a Piper diagram (Figure 6.7), which shows the relative contribution of major cations and anions on a mill equivalent basis to the total ion content of the water. Calcium and magnesium is the dominant cations in all water types, except cluster 1.

Cluster 1

The first hydrochemical cluster is typified by a Na-HCO₃-SO₄ and Na-Ca-HCO₃ type of water. Sodium is the major cation, and bicarbonate is the dominant anion with a concentration of about 61% and 73 % of the total cations and anions respectively. In this group, sulphate is found in considerable amounts reaching up to 17 % of the total anions. This hydrochemical cluster has typical characterized by its high TDS and EC values between 1325 and 1504 μS/cm. Groundwater samples from east and north east corner of the valley are grouped in this cluster.

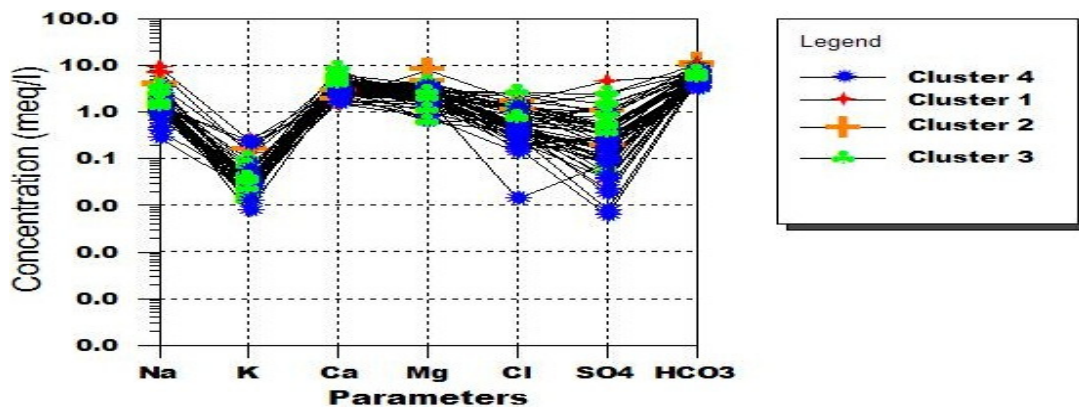
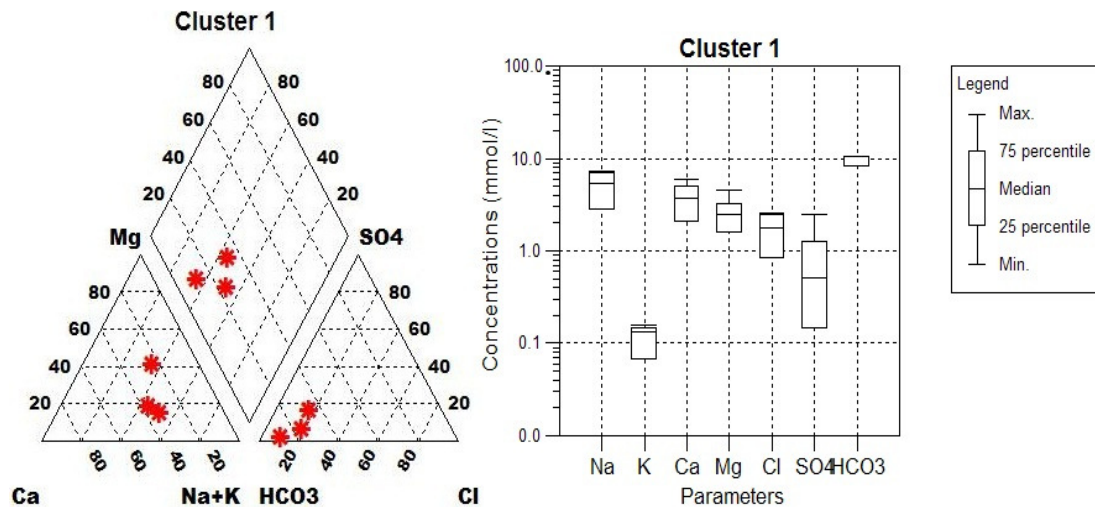


Figure 6.6: Scholler diagram of data presentation: This is clearly that the concentration of Cl⁻ and SO₄²⁻ anions and Na⁺ cation increases towards the discharging zone.



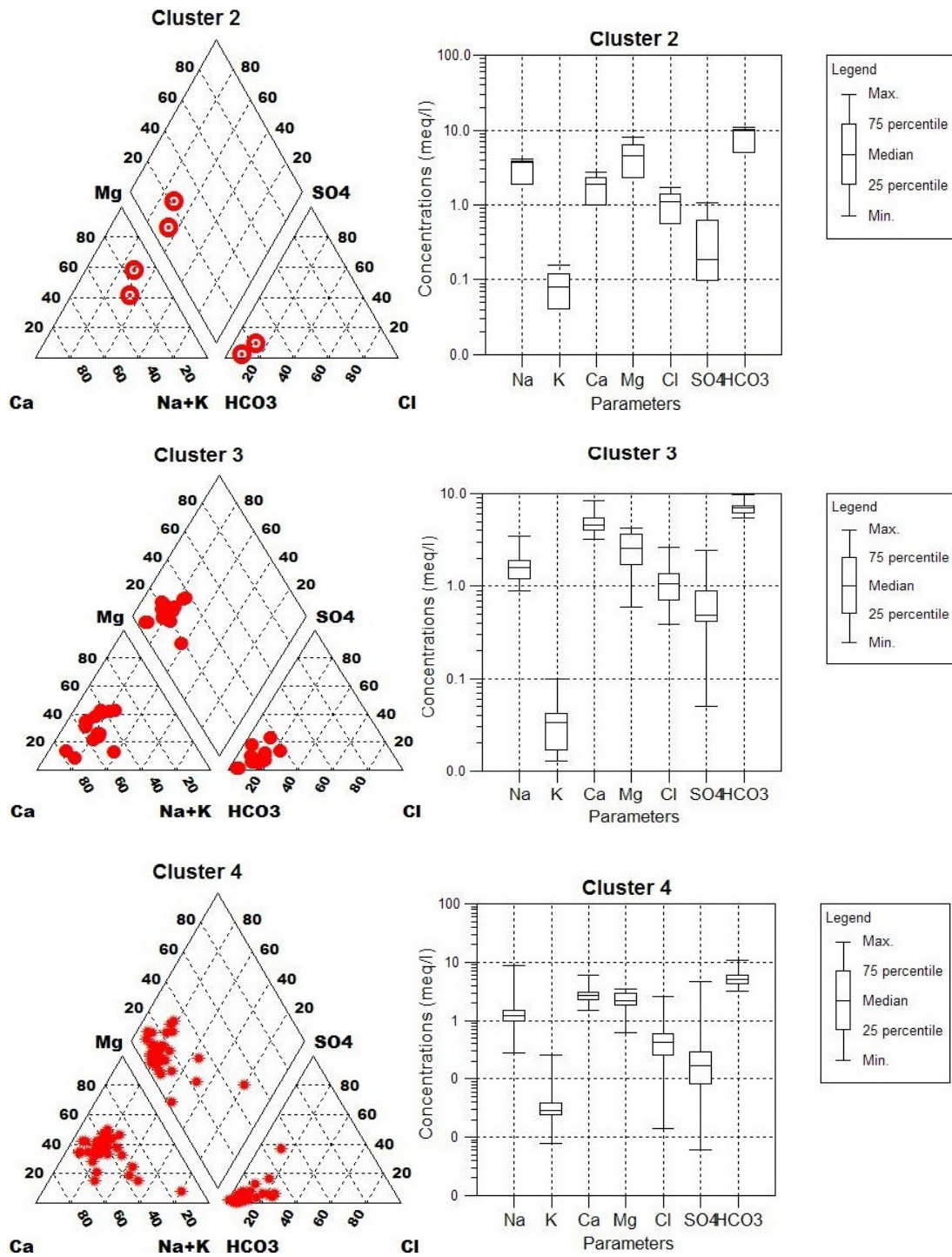


Figure 6.7: Piper plot of hydrochemical clusters and their statistical summary

Cluster 2

The second cluster is identified by typical Mg-Na-HCO₃ and Mg-Na-Ca- HCO₃ type of water. The water samples which fall under cluster 2 have high PH, TDS and EC values.

Magnesium and bicarbonate are the dominant cation and anion, and the concentration of bicarbonate is about 88 % of the total anions.

The groundwater samples in this cluster are springs collected from the eastern part of the study area. The salinity of groundwater in cluster 1 and 2 could be due to longer subsurface resident time of groundwater system.

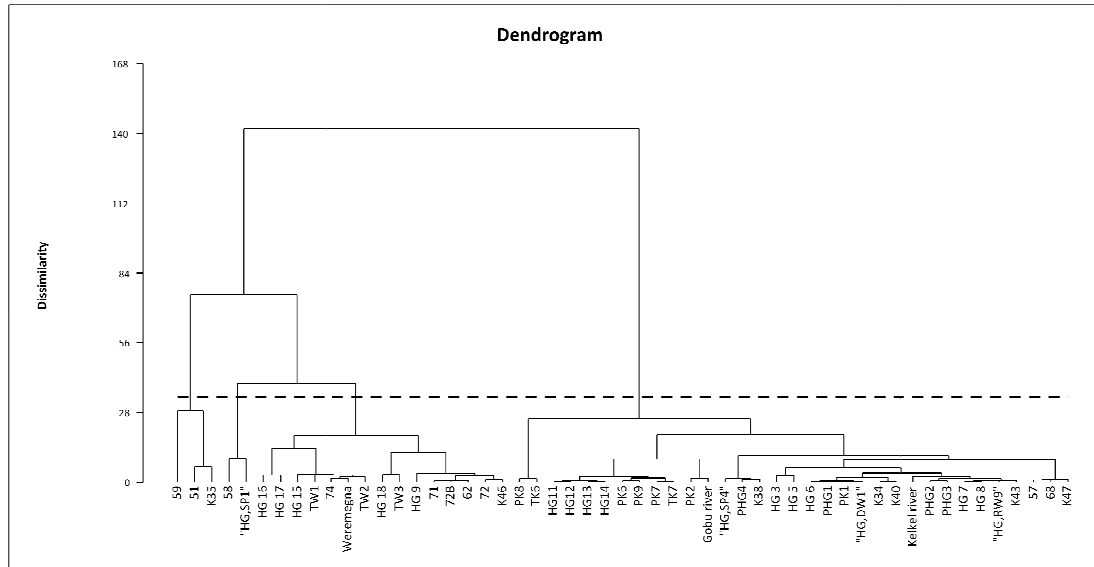


Figure 6.8: HCA classification of water samples using XLSTAT.

Cluster 3

About 30% of the samples are clustered in this group. Ca-Mg-HCO₃, Ca-HCO₃ and Ca-Mg-Na-HCO₃ are the dominant water type in this cluster. Calcium and magnesium are the major cations and bicarbonate is the major anion of the total anions. Chloride also found in a considerable amount. Water samples grouped under this cluster are relatively lower PH value and higher TDS Recorded. Most of this group samples located on the central and south tip of the valley.

Cluster 4

More than 60% of samples collected are included in this cluster. This hydrochemical cluster dominantly consists of groundwater with Mg-Ca-Na-HCO₃, Mg-Ca-HCO₃, Ca-Mg-HCO₃, and Ca-Mg-Na-HCO₃ type. The River water sample in the valley is classified as Ca-Mg-HCO₃ type, which is similar to hydrochemical behavior of groundwater in the basins. The conductivity and TDS of these clusters have relatively lower than the above clusters. Bicarbonate is the principal anion with concentrations about 90% of the total anions. The groundwater systems in this cluster are located in the western and northern part of the valley.

Cluster	EC (25 ⁰ c) μS/cm	pH	Na	K	Ca	Mg	Cl	SO4	HCO ₃
Cluster1	1445.3	7.5	176.9	5.1	82.0	23.3	77.7	127.3	563.5
Cluster2	1046.5	8.1	89.7	3.1	46.7	76.8	49.5	30.0	620.6
Cluster3	867.7	7.5	39.7	1.3	97.1	33.6	39.6	35.8	435.2
Cluster4	531.1	7.7	27.4	1.3	51.8	27.4	16.0	8.3	306.1

Table 6.3: Mean concentrations (unit in mg/l) for clusters derived from HCA

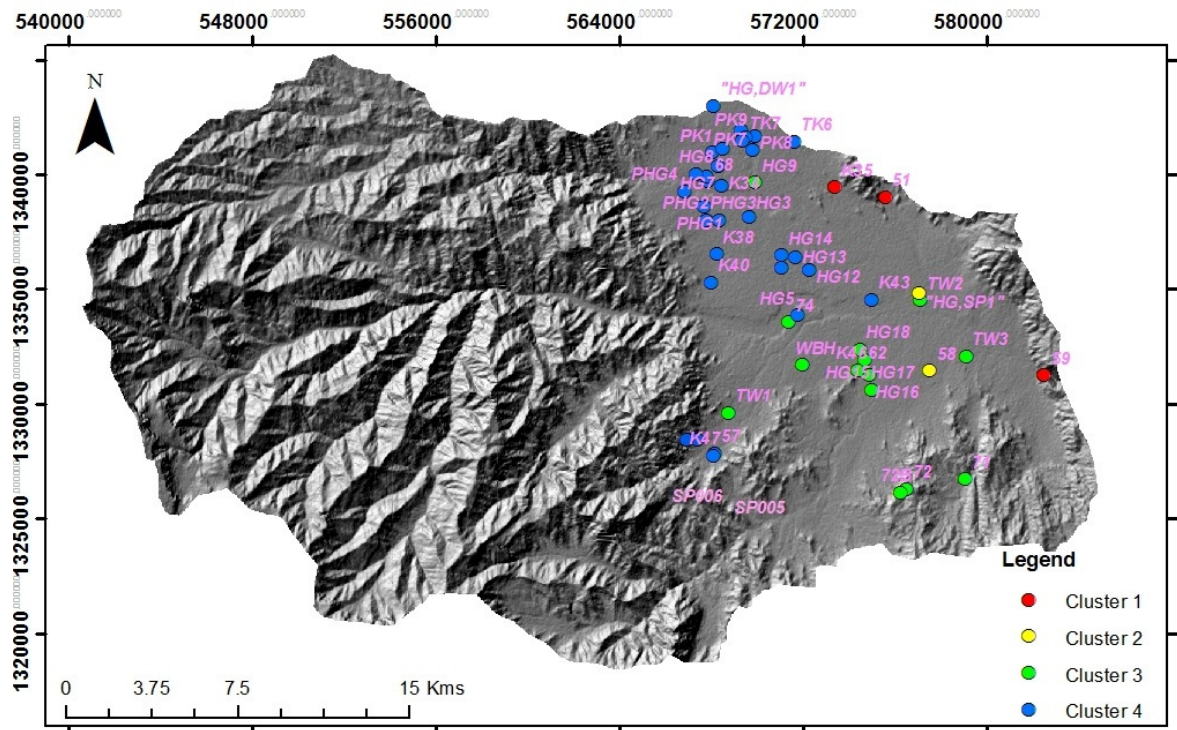


Figure 6.9: Spatial distribution of different class of water

6.5. GROUNDWATER CHEMISTRY

The majority of groundwater samples falls into the Ca-Mg-HCO₃ or Mg-Ca-HCO₃ type in the Piper plot (figure 6.7), as the dominating cation is Calcium (Ca⁺) and Magnesium (Mg⁺), while bicarbonate (HCO₃⁻) is the principal anion.

The majority of the springs, hand dug wells and boreholes water samples in the plain close to western highland escarpment are Ca-HCO₃/ Ca-Mg-HCO₃ type indicating this area receives high recharge. The stream sample also showed Ca-Mg-HCO₃ type. The northern and central parts of the valley groundwater system show intermediate nature of Ca-Mg-Na-HCO₃ water type, while the eastern part of the valley groundwater is Na-Ca-HCO₃/Na-HCO₃-SO₄ types.

Due to groundwater recharge from rainfall and low groundwater residence time the TDS is mostly less than 500 mg/l in the highland/escarpments. The high Ca and Mg content in the highlands are related to the dominance of the basic volcanics (basalt). In the general groundwater chemical evolution model (Plummer et al., 1990; Adams et al., 2001; Edmunds and Smedley, 2000) as cited in Ayenew et al., 2009, these types of waters are often regarded as recharge area waters which are at their early stage of geochemical evolution. They are rapidly circulating groundwater which has not undergone a pronounced water-rock interaction.

The total ionic enrichment follows the groundwater flow path from the western highland escarpment toward the eastern tip of the of the study area, in general graphical analysis showed that there are three types of groundwater i.e. The first type Ca-Mg-HCO₃, the second type intermediate nature Ca-Mg-Na-HCO₃ type and the third Na-Ca-HCO₃ types as distinctively shown on the Stiff Diagram (Figure 6.12).

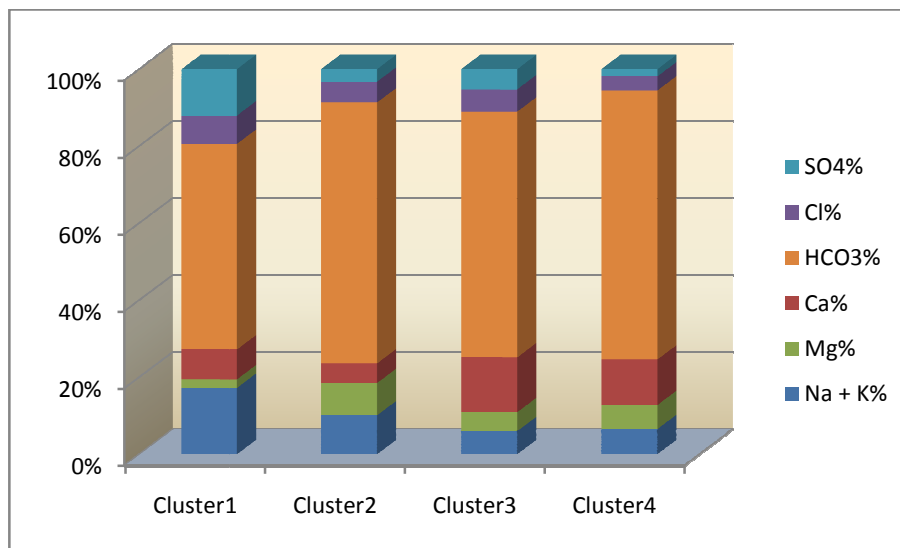


Figure 6.10: Collins bar diagram: This is clearly that the concentration of Cl⁻ and SO₄²⁻ anions significantly increases towards the discharging zone.

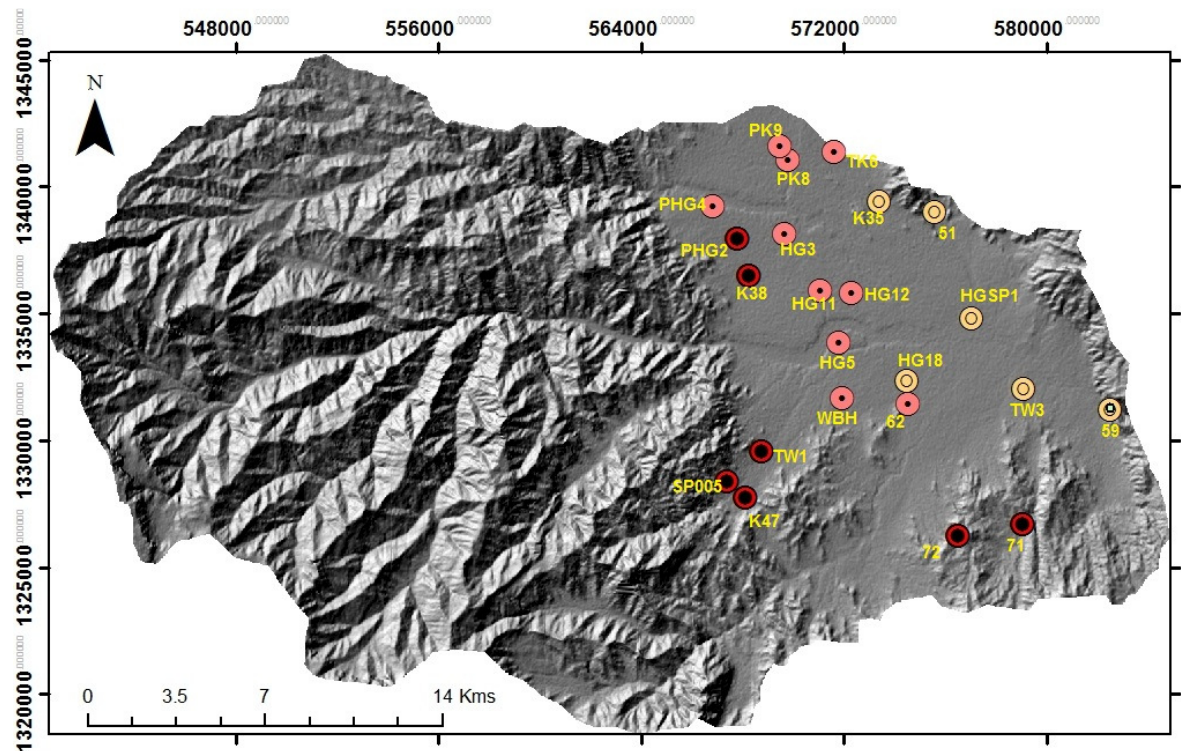
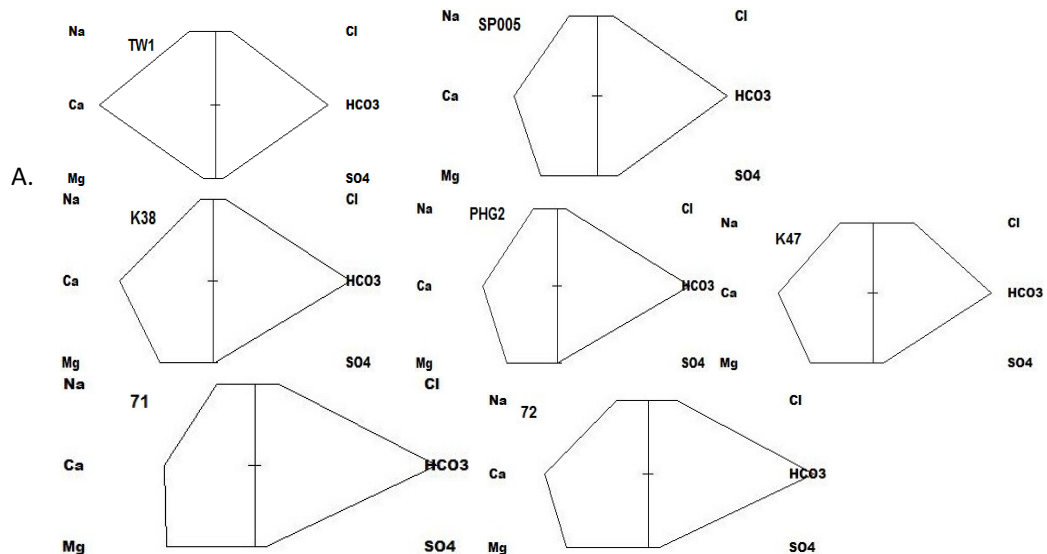


Figure 6.11: Groundwater geochemical evolution in the basin: location of sample points used for stiff diagram in figure 6.12. As indicated in the stiff plot, Ca-Mg-HCO₃ dominated groundwater system changes to Ca-Mg-Na-HCO₃ and Na-Ca-HCO₃ groundwater system when one goes from the western part of the watershed to the eastern part.



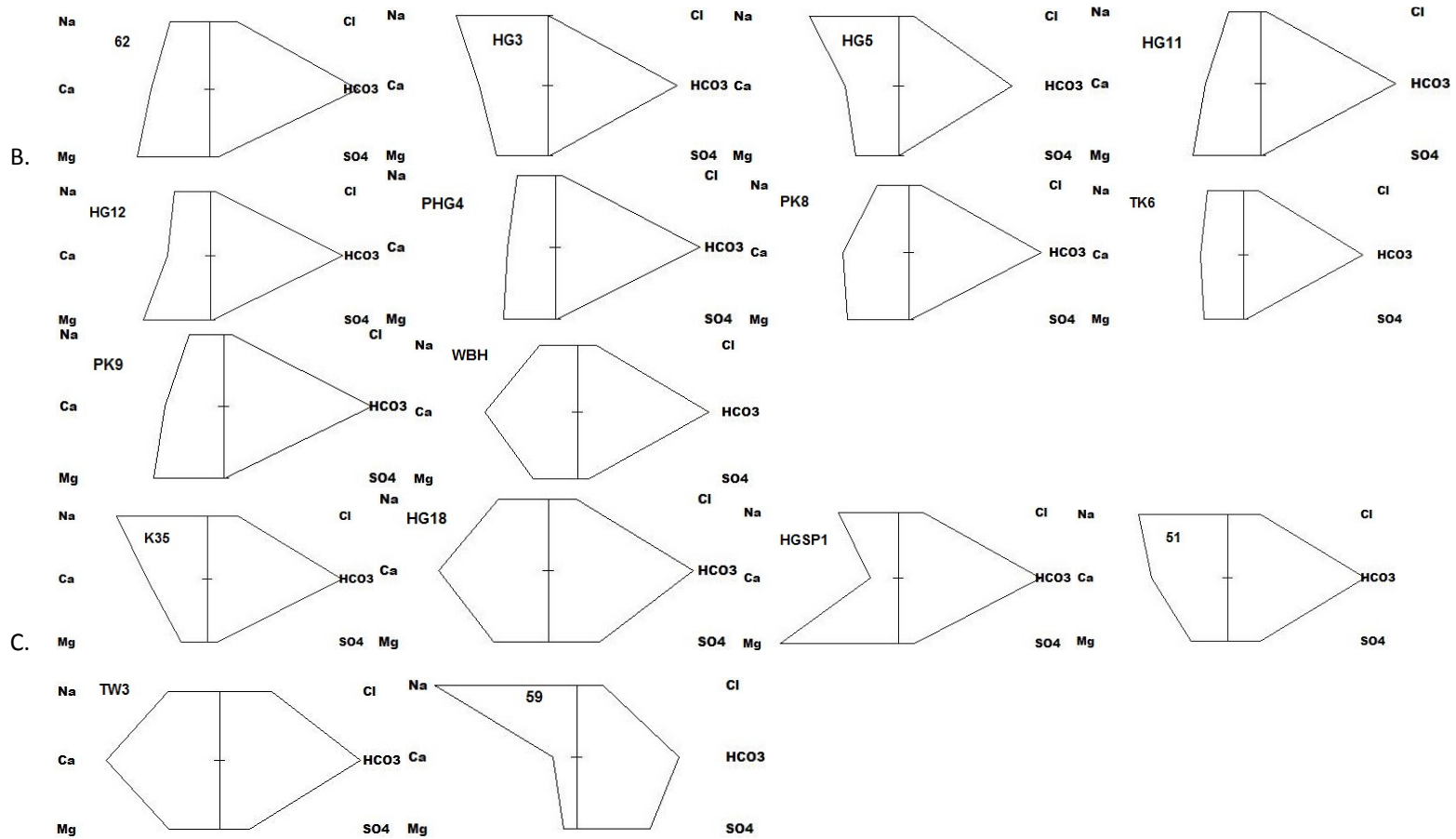


Figure 6.12: Stiff diagram of Kobo valley groundwater: (A) groundwater sample shows the recharge area water (western part of the valley), (B) intermediate water type from northern and central part of the valley and (C) concentrated groundwater in eastern part of the valley.

6.6. WATER QUALITY ASSESSMENT

In water resource potential evaluation, the quality of water is as important as the quantity. Groundwater is mainly used for drinking, irrigation and industrial purposes. Therefore, quality criteria depend on the use of water for a particular purpose, and quality standards have to be maintained in water supply for different uses to avoid deleterious effects. In this section the quality of water assessed from drinking water point of view and from agricultural point of view.

6.6.1. DRINKING WATER QUALITY ASSESSMENT

Groundwater forms an important source of water for drinking and other domestic purposes. Therefore, groundwater, in general, is safer for use than surface water especially from the point of view of bacterial pollution; but the chemical composition of water is also important, as certain chemical constituents become toxic beyond a particular concentration, although they may be beneficial in lower amounts.

Prescribed standards for drinking-water vary from country to country, depending upon economic conditions, climate, food habits and geographic location. There is also conflicting evidence with respect to safe limits for certain constituents.

The chemical analysis results from the water samples in the study area have been evaluated and compared with WHO (2008) and Ethiopian guideline values for water quality standards to observe the level of pot ability of the water with respect to some major ionic constituents like Fluoride, sodium, chloride, sulfate and etc that are the major threat in relation to health problem. As can be seen from water quality data, the major anions and cations of most of the sampled water fall with the range of WHO and Ethiopian guideline values.

Table 6.4: Comparison with water quality standards for drinking water

Element	WHO guideline mg/l	Total% of water samples above WHO guideline	Ethiopian guide line mg/l	Total% of water samples above Ethiopian guideline
Fluoride	1.5	1.9	3	0
Sodium	200	1.9	358	0
TDS*	1000	1.9	1776	0
Chloride	250	0	533	0
Sulfate	500	0	483	0
Nitrate	50	5.7	50	5.7

*WHO guideline (1984)

6.6.2. WATER QUALITY FOR IRRIGATION PURPOSES

Irrigated agriculture is dependent on an adequate water supply of usable quality. Just as any water is not suitable for human beings, in the same way, any water is not suitable for plant life. Water containing impurities, which are injurious to plant growth, is not satisfactory for irrigation, and called unsatisfactory water.

Water quality for agricultural purposes is determined on the basis of the effects of the water on the quality and yield of the crops, as well as the effects on drainage efficiency and characteristic changes in the soil (Wilcox, 1955). The quality standards for irrigation water are based on: (1) total dissolved solids which may affect the intake of water and other nutrients by plants through osmosis; (2) the relative concentration of alkalis and alkaline earths which affect the soil texture due to cation exchange, and thereby its permeability and drainage characteristics; and (3) the concentration of specific ions, viz. boron, selenium, cadmium etc., which are toxic to the growth of plants beyond certain levels.

Soil scientists use the following categories to describe irrigation water effects on crop production and soil quality:

- Salinity hazard - total soluble salt content
- Sodium hazard - relative proportion of sodium (Na^+) to calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions
- pH
- Alkalinity - carbonate and bicarbonate
- Specific ions: chloride (Cl), sulfate (SO_4^{2-}), boron (B), and nitrate-nitrogen ($\text{NO}_3\text{-N}$).

Other potential irrigation water contaminants that may affect suitability for agricultural use include heavy metals and microbial contaminants.

6.6.2.1. SALINITY HAZARD

The most influential water quality guideline on crop productivity is the water salinity hazard as measured by electrical conductivity (EC_w). The primary effect of high EC_w water on crop productivity is the inability of the plant to compete with ions in the soil solution for water (physiological drought). The higher the EC, the less water is available to plants, even though the soil may appear wet. Because plants can only transpire "pure" water, usable plant water in the soil solution decreases dramatically as EC increases.

Table 6.5: Suggested criteria for irrigation water use based upon conductivity.

Classes of water	Electrical Conductivity($\mu\text{S/cm}$)
Excellent	≤ 250
Good	250 – 750
Permissible ¹	750 – 2000
Doubtful ²	2000 – 3000
Unsuitable ²	≥ 3000

¹Leaching needed if used, ²Good drainage needed and sensitive plants will have difficulty obtaining stands. (Sources: Bauder et. al., 2003)

Based on EC as an index of salinity hazard (table 6.5), the water samples of the study area can be classified as follows:

Table 6.6: Suitability of groundwater in the study area for irrigation based on EC

Water samples	Ranges of EC ($\mu\text{S/cm}$)	Water class
HG,DW1,HG,RW7,HG,RW8,004SP, 006SP, 57, 68, HG1, HG2, HG3, HG5, HG6, HG7, HG8, HG10, HG11, HG12, HG13, HG14, HG15, TW1, K34, K37, K38, K40, K43, K47, PHG1, PHG2, PHG3, PHG4, PK1, PK2, PK6, PK7, PK8,PK9, TK6, TK7, Weremgna BH, Hormat river, Kelkel River	314- 687	Good
HG,SP1, 003SP, 005SP, 58, 59, 71, 72, 72B, 74, 62, 51, HG9, HG16, HG17, HG18, TW2, TW3, K35, K46	787-1584	Medium/ permissible

6.6.2.2. SODIUM HAZARD

While EC_w is an assessment of all soluble salts in a sample, sodium hazard is defined separately because of sodium's specific detrimental effects on soil physical properties. The sodium hazard is typically expressed as the sodium adsorption ratio (SAR). This index quantifies the proportion of sodium (Na^+) to calcium (Ca^{++}) and magnesium (Mg^{++}) ions in a sample. Calcium will flocculate (hold together), while sodium disperses (pushes apart) soil particles. This dispersed soil will readily crust and have water infiltration and permeability problems. General classifications of irrigation water based upon SAR values are presented in Table 6.7.

$$SAR = \frac{Na+meq/l}{\sqrt{\frac{(Ca^{++}meq/l)+(Mg^{++}meq/l)}{2}}}$$

Table 6.7: General classification of water sodium hazard based on SAR values.

SAR values	Sodium hazard of water	Comments
1-9	Low	Use on sodium sensitive crops must be cautioned.
10-17	Medium	Amendments (such as gypsum) and leaching needed.
18-25	High	Generally unsuitable for continuous use.
≥26	Very High	Generally unsuitable for use.

(Sources: Bauder et. al., 2003)

However, many factors including soil texture, organic matter, crop type, climate, irrigation system and management impact how sodium in irrigation water affects soils. Additionally, at the same SAR, water with low EC_w (salinity) has a greater dispersion potential than water with high EC_w.

Table 6.8: suitability of Groundwater of the study area for irrigation purpose based on SAR

Water samples	Range of SAR	Water class
HG,DW1, HG RW7, HGRW8, HGSP1, HGSP4, HG3, HG5, HG6, HG7, HG8, HG9, HG11, HG12, HG13, HG14, HG15, HG16, HG17, HG18, TW1, TW2, TW3, PHG1, PHG2, PHG3, PHG4, PK1, PK2, PK6, PK7, PK8, TK6, TK7, K34, K35, K38, K40, K43, K46, K47Hormat river, Kelkel River	0.11-784	Excellent

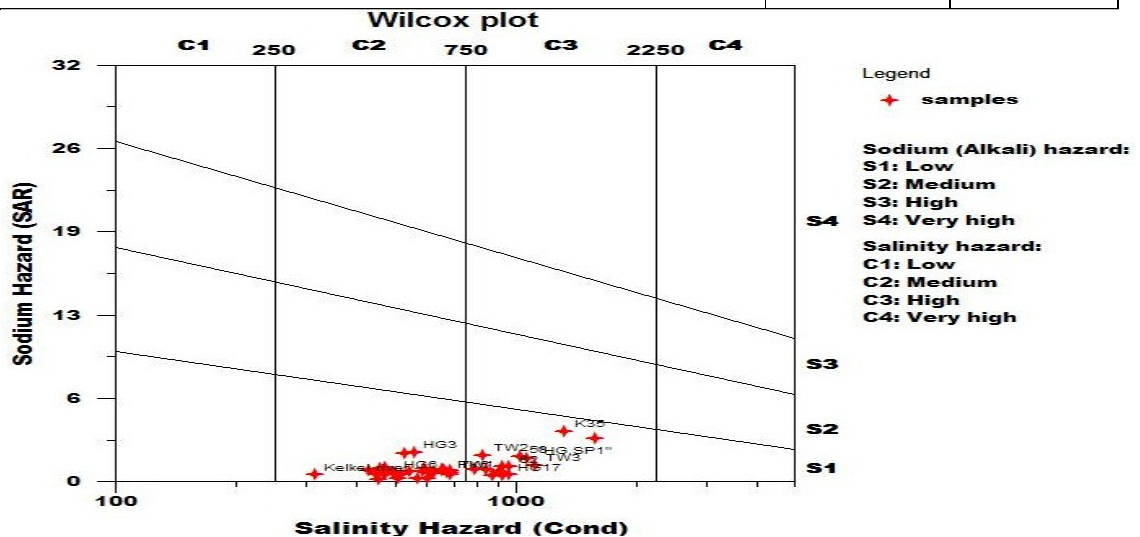


Figure 6.13: irrigation water classification on samples collected from Kobo valley

6.6.2.3. TOXICITY PROBLEMS

Toxicity problems occur if certain constituents (ions) in the soil or water are taken up by the plant and accumulate to concentrations high enough to cause crop damage or reduced yields. The degree of damage depends on the uptake and the crop sensitivity. The

permanent, perennial-type crops (tree crops) are the more sensitive. Damage often occurs at relatively low ion concentrations for sensitive crops. It is usually first evidenced by marginal leaf burn and interveinal chlorosis. If the accumulation is great enough, reduced yields result. The more tolerant annual crops are not sensitive at low concentrations but almost all crops will be damaged or killed if concentrations are sufficiently high.

The ions of primary concern are chloride, sodium and boron. Although toxicity problems may occur even when these ions are in low concentrations, toxicity often accompanies and complicates a salinity or water infiltration problem.

Chloride (mg/l)	Effect on Crops
Below 70	Generally safe for all plants.
70-140	Sensitive plants show injury.
141-350	Moderately tolerant plants show injury.
Above 350	Can cause severe problems.

Chloride tolerance of selected crops. Listing in order of increasing tolerance: (low tolerance) dry bean, onion, carrot, lettuce, pepper, corn, potato, alfalfa, sudangrass, zucchini squash, wheat, sorghum, sugar beet, barley (high tolerance). Source: Mass (1990).

The chloride concentration of the borehole samples in the study area except (TW3) is suitable for irrigation from the point of toxicity.

Figure 6.14: Na concentration distribution in groundwater of Kobo valley

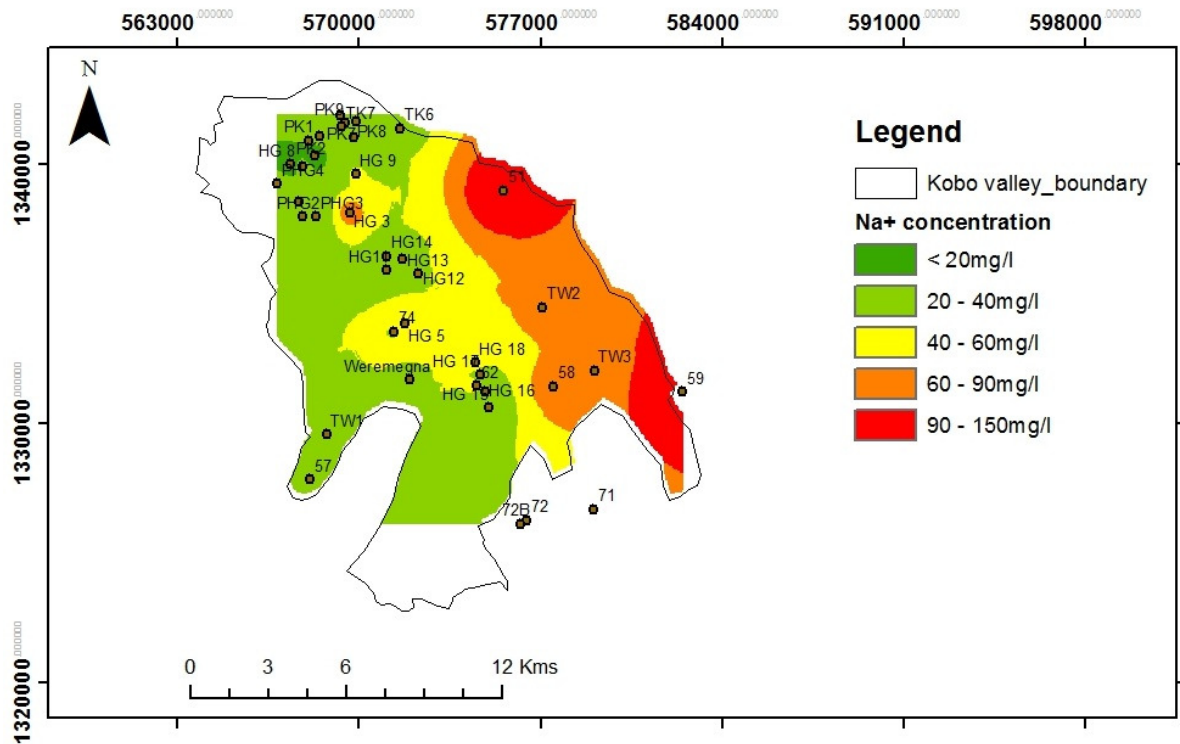


Figure 6.15: HCO₃ concentration distribution in groundwater of Kobo valley

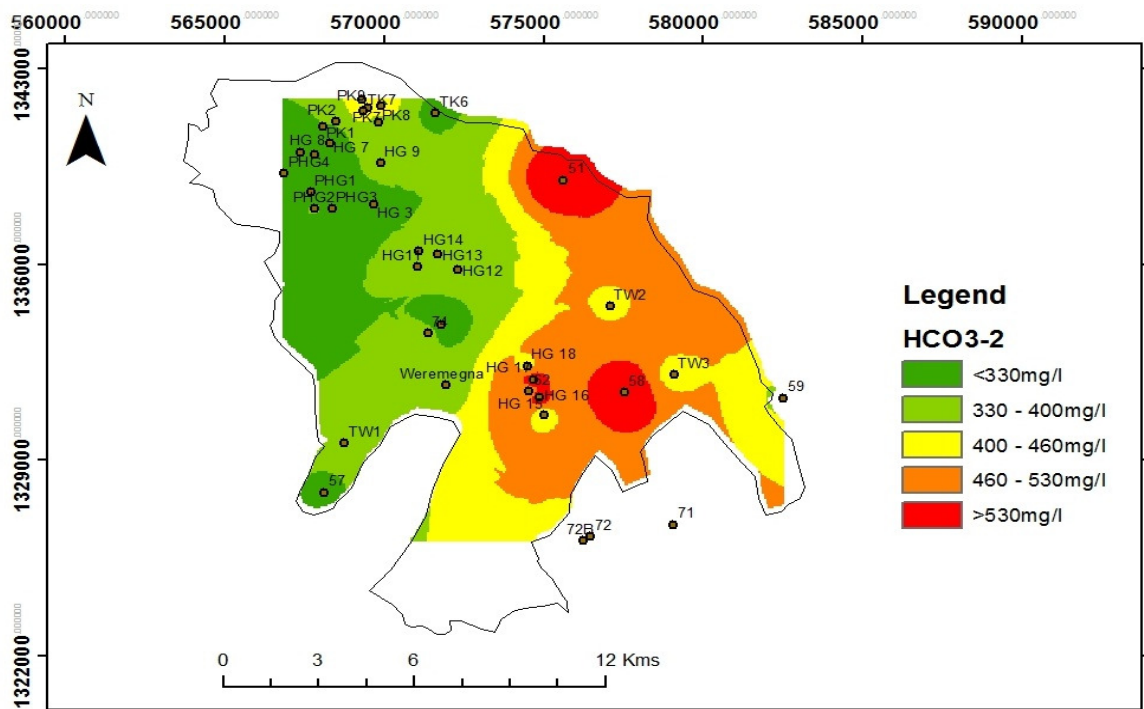


Figure 6.16: Cl concentration distribution in groundwater of Kobo valley

Groundwater Potential evaluation and flow dynamics of Hormat-Golina River catchment, Kobo Valley

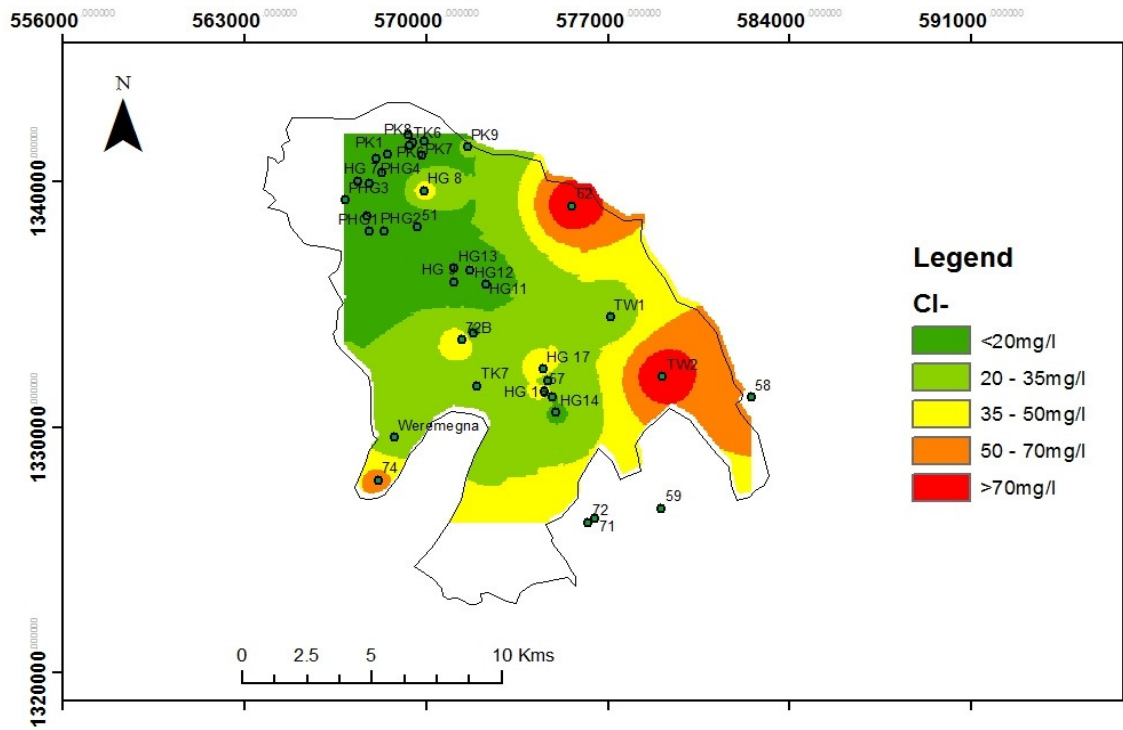
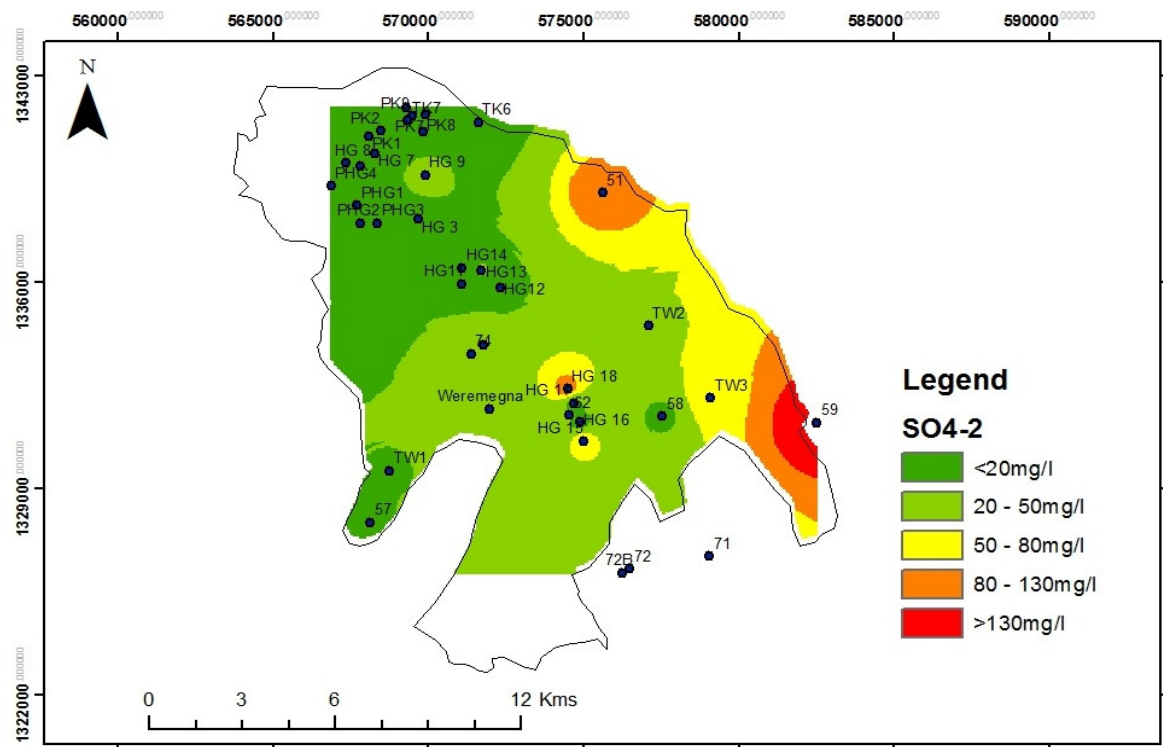


Figure 6.17: SO₄ concentration distribution in groundwater of Kobo valley



CHAPTER SEVEN

7. CONCLUSION AND RECOMMENDATION

7.1. CONCLUSION

Hormat-Golinal River basin (Kobo Valley) is found in Northern Ethiopia, it covers area of about 806Km² and made up of an asymmetric graben structure. It has an axial length about 42Km and a width of about 21Km. The landform includes a plateau on the highlands (65%) that ranges from 2050 m to 3600 m a.m.s.l, steep escarpments (20%) ranging from 1680 m to 2050 m a.m.s.l, and the valley floor (17%) with an elevation from 1304m to 1680 m. a.m.s.l. it has one perennial river (Golina) feed by two intermittent tributary called Hormat and kelkeli streams.

The river catchment has two climatic zones. The mountains and the escarpments characterized humid while the valley part of the area is characterized with semi arid climatic zones. The western highland part of the area receives relatively higher precipitation 910 mm and the valley receives 739 mm precipitation. The area shows bimodal rainfall pattern. The long term minimum and maximum temperatures of Kobo valley are 11⁰C and 34.3⁰C respectively.

Since the penman method take in to account several climatic factors to compute PET, it is considered to be the most reliable method. For comparison different methods have been examined and compared. Estimation of annual Potential Evapotranspiration by Penman method for Kobo plain is 1596.1 mm. For the same plain the Thornthwaite formula underestimated by 31%, while the Hargreaves method give close estimation to that of the Penman with only 15% higher values.

The Actual Evapotranspiration of the area was calculated using Turc empirical method and Thornthwaite and Mother Methods (soil water balance method). AET for the whole catchment using Turc empirical method and soli water balance method are 655mm and 982.8mm respectively. The value obtained by Turc emperical method is assumed to be the AET of the area.

The hydrogeological mapping was performed by classifying the Hydrogeological units based on surface geology, borehole lithologic log, pumping test geophysical information and remote sensing data of the area. In the study area majorly there are two aquifer units; unconsolidated sediment aquifer (Quaternary colluvial and alluvial deposit, interfluvial, fan foot plains and valley bottom Quaternary deposits, and central valley flood plain

Quaternary deposits (lacustrine deposit) and volcanic rock aquifer. From which the most productive aquifer Quaternary colluvial and alluvial deposit aquifer situated at the foot of western escarpment.

Type of aquifers is distinguished using three integrated approach; observing lithological logs of wells, construction of diagnostic (log – log) plot and specialized plot (semi – log) plot of drawdown versus time and by careful observation of static/piezometric water level with respect to the water bearing horizon. In the valley area unconfined, confined and leaky types of aquifers are identified. More than 70% of wells analyzed are unconfined aquifers. The hydraulic parameters of the Western Mountain and plateau cannot be determined due to the absence of wells.

The data of 39 aquifer pumping tests were analyzed with appropriate method. The transmissivity ranges from 6.85 – 4510 m²/d. The wells tapping the Interfluvial, Fan Foot Plains deposits, and the Central Valley Flood Plain Quaternary deposits, have the lowest values for the transmissivity (<250 m²/d), whereas the wells tapping the colluvial deposits and the Quaternary alluvial deposits in the western part of the area at the foot of the mountains shows the highest transmissivity values (up to 4320 m²/d). The hydraulic conductivity also ranges from 0.19 – 125 m/d and Hydraulic conductivity is high in the western side of the graben than the central and eastern side of catchment. There is a close relationship between the recorded specific capacity and transmissivity values, based on data from 37 wells. The best fit regression equation through the data pairs is $T = 0.529Sc + 157.7$ with a goodness of fit ($R^2 = 0.79$) and for log transformed values the best fit regression equation through the data pairs is $T = 1.200Sc - 0.711$ with a goodness of fit ($R^2 = 0.82$).

Regarding the groundwater recharge and discharge zone of the area, direct recharge in to groundwater is insignificant in the central and eastern part of the graben. This is not due to high evaporation rate and low permeability of lacustrine sediments. However, the contribution of tectonic structure particularly fault/fractures that cross east to west of the study area may have significant role in downward movements of water from water bodies that accumulated during flood period particularly at the downstream Hormat and Kelkeli river. In general groundwater recharge to the Kobo graben is from direct percolation through colluvial and alluvial deposits at the western tip of the graben and from western and eastern highlands and escarpment through discontinuities particularly faults/joints striking NNE-SSW, ENE-WSW from Zoble ridges and N-S from Lasta Mountains dipping towards the plane. A plot of contours of the hydraulic heads and the stream networks reveal that

Golina River and its tributary have a behavior of gaining from the aquifer in the downstream.

Groundwater flow direction is generally from west to east except that there are localized flow components observed in the vicinity of elevated hills, boundaries of the basin and along the river banks.

Three different methods had been adopted based on the availability of data to estimate the groundwater recharge of the catchment which is used to plan how to use the resource without harming. The methods include chloride mass balance (30MCM), conventional water balance methods (74.15MCM) and Darcy approach (30.2MCM). The average of the three values is taken as the recharge of the area (44.8MCM) which is 6.4% of the total precipitation of the catchment.

The hydrochemical analysis of water samples in the area revealed that the water samples from deep wells and springs adjacent or close to the western highland escarpment have relatively lower values of TDS, EC, PH, sodium, chloride etc. Generally, the ion concentrations increase when one is moving from the highland escarpment to the central part of the graben indicating the increased dissolution along the flow paths from recharge to discharge areas. The piper plot of the water chemical analysis shows that shallow wells, bore holes and spring water samples are Ca-Mg-HCO₃ or Mg-Ca-HCO₃ type in the recharge area, intermediate water type Ca-Mg-Na-HCO₃ in northern and central part of the valley to Na-Ca-HCO₃ type towards the east. The Multivariate Statistical method is also in very close agreement classified the water samples in to four classes. The water sample which are classified under class 1 and class 2 are from the east, northeast and north of the graben, which are from the discharge zone, most of the samples grouped under cluster 3 and 4 located on the central and western part the graben respectively which is closer to the recharge area.

In general for most of the major constituents the samples show concentrations below the maximum allowable limits (WHO guide line) i.e., the borehole waters could be used safely for drinking. From agricultural point of view; the groundwaters in Kobo valley are low in the sodium adsorption ratio (SAR) values making them favorable for irrigation. The main danger posed with respect to irrigation is the medium to high values of salinity as evidenced by the conductivity measurements.

7.2. RECOMMENDATION

- Since there is many borehole data over the valley floor and nothing in the western and eastern highland/ escarpment (i.e. volcanic aquifer), some additional well drilling tests could give a good picture of permeability, productivity and thickness of the volcanic aquifer unit which are highly related to groundwater potential evaluation of the study area.
- Stream flow along the outlet (Golina River) and other main streams should be gauged, as it is useful to establish the basin water balance and identify where, and how much, the river gain from and lose to groundwater. Also only one meteorological station is available in the catchment, there should be establish other station in highland part.
- No observations have been made on the groundwater level fluctuation to make some assessment from groundwater hydrograph. There should be drilled piezometes and fitted with automatic recorders.
- Kobo valley is being developed for large scale irrigation project, care should be taken related to usage of pesticides, over fertilizing and over irrigating that causes groundwater contamination.
- Artificial recharge should be practiced to enhance the groundwater resource.
- For further groundwater resource development plans in the valley, it is important to take into account the balance between the groundwater recharge and the intended abstraction rates both for irrigation and domestic water supply to ensure the sustainability of the resource in the valley. Moreover, it is also important to consider the boreholes' separation distance.

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APPENDICES

Appendix 1: Location and pumping test data of the boreholes

No	Well Id	X	Y	Z	Ob.well	depth (m)	SWL (m)	yield (l/s)	aquifer type	Test method	Tav (m ² /d)	Kav (m/d)	T classified as	K classified as	
1	PHG1	567688	1338578	1487		129	25	50	Unconfined	Neuman (1975)	1730	32.7	very high	very high	
					PHG1-OB1	150	19								
2	PHG2	567801	1337977	1477		108	19	50	Unconfined	Neuman (1975)	4510	125	very high	very high	
3	PHG3	568356	1337982	1472		156	17	50	Confined	Theis (1935)	472	8.07	Medium	medium	
					PHG3-OB1	182	16								
4	PHG4	566854	1339244	1510		116	29	50	Unconfined	Neuman (1975)	2040	49.9	very high	very high	
					PHG4-OB1	128	29								
5	PHG5	571398	1335248	1432		155	29	57	Unconfined	Neuman (1975)	118	2.81	low	low	
6	PHG6	571821	1334963	1426		178	29	58.5	Unconfined	Neuman (1975)	450	9.78	Medium	medium	
					PHG6-OB1	178	29								
7	PHG7	572289	1334951	1419		180	29	51.6	Unconfined	Neuman (1975)	255	4.25	Medium	low	
8	PHG8	570553	1334124	1447		147	29	46.4	Unconfined	Neuman (1975)	282	5.89	Medium	medium	
9	PHG9	570089	1333952	1456		158	29	53.5	Confined	Theis (1935)	1020	21.4	very high	very high	
					PHG9-OB1	162									
10	PHG10	569560	1334010	1462		146	25	59.5	Unconfined	Neuman (1975)	1790	42.6	very high	very high	
						118	16	32							
						THG1-OB1	137	16							
11	THG1	576123	1336656	1384		122	17		Unconfined	Neuman (1975)	164	5.47	low	medium	
						THG1-OB2	122	17							
							212	3.1							57
12	THG3	575801	1333260	1385		219	2.7		Confined	Theis (1935)	622	10	high	high	
						THG3-OB1	219	2.7							
						THG3-OB2	253	1.7							
13	THG4	575471	1331124	1408		175	5.2	62	Confined	Theis (1935)	748	15.6	high	high	
						THG4-OB1	190	5.8							
						THG4-OB2	162	6.7							
14	Pk1	568066	1340931	1491		134	26	55	Leaky	Hantush (1955)	286	5.96	Medium	medium	
					Pk1-Ob1	170	26								
					Pk1-Ob2	151	25								
15	Pk2	568476	1341101	1487		137	24	80	Leaky	Hantush (1955)	330	6.1	Medium	medium	
						PK2-OB1									

Groundwater Potential evaluation and flow dynamics of Hormat-Golina River catchment, Kobo Valley

No	Well Id	X	Y	Z	Ob.well	Depth (m)	SWL (m)	yield (l/s)	aquifer type	Test method	Tav (m ² /d)	Kav (m/d)	T classified as	K classified as
16	Pk6	569299	1341890	1481		145	18	40	Unconfined	Neuman (1975)	267	4.87	Medium	low
					PK6-OB1									
17	Pk7	569892	1341651	1473		183	21	40	Confined	Theis (1935)	664	1.02	High	low
					PK7-OB1									
18	Pk8	569814	1341065	1466		181	19	50	Confined	Theis (1935)	199	2.61	Low	low
					PH8-OB1									
19	Pk9	569485	1341610	1476		145	25	50	Unconfined	Neuman (1975)	756	14.3	High	high
					Pk9-Ob1	128	35							
20	Tk7	569334	1341467	1474		168	15	50	Confined	Theis (1935)	420	6.36	Medium	medium
					Tk7-Ob1	160	14							
21	HG1	568082	1338941	1480		112	21	51	Unconfined	Neuman (1975)	88.5	2.46	very low	low
22	HG2	569450	1338823	1461		91	15	52	Unconfined	Neuman (1975)	112	3.12	Low	low
23	HG3	569659	1338130	1455		111	15	22	Unconfined	Neuman (1975)	22.8	0.633	very low	low
24	HG4	569354	1339493	1465		109	17	51	Unconfined	Neuman (1975)	122	3.39	Low	low
25	HG5	571782	1333845	1429		112	20	50	Unconfined	Neuman (1975)	104	2.89	Low	low
26	HG6	567804	1339909	1495		101	25	52	Unconfined	Neuman (1975)	154	4.29	Low	low
27	HG7	568283	1340339	1487		106	21	50	Unconfined	Neuman (1975)	56	1.56	very low	low
28	HG8	567346	1340010	1502		110	27	50	Unconfined	Neuman (1975)	130	3.62	Low	low
29	HG9	569905	1339618	1461		100	26	12	Unconfined	Neuman (1975)	6.85	0.19	very low	low
30	HG10	570348	1339366	1455		100	24	34	Unconfined	Neuman (1975)	34.3	0.953	very low	low
31	HG11	571055	1335915	1437		117	14	50	Unconfined	Neuman (1975)	84.6	2.02	very low	low
32	HG12	572295	1335804	1416		110	16	50	Confined	Theis (1935)	244	5.8	Low	medium
33	HG13	571683	1336365	1424		111	16	50	Confined	Theis (1935)	273	6.51	Medium	medium
34	HG14	571067	1336466	1436		109	17	50	Unconfined	Neuman (1975)	142	3.38	Low	low
35	HG15	574997	1330600	1412		117	8	50	Unconfined	Neuman (1975)	165	3.92	Low	low
36	HG16	574865	1331232	1412		99	8.5	25	Unconfined	Neuman (1975)	47.4	1.32	very low	low
37	HG17	574673	1331879	1405		120	10	50	Unconfined	Neuman (1975)	95.9	2	very low	low
38	HG18	574474	1332360	1399		119	9.3	50	Unconfined	Neuman (1975)	93.3	1.94	very low	low
39	Werem egna	571945	1331680	1561		110	35	8	Unconfined	Neuman (1975)	104	2.17	Low	low

Appendix 2: Analysis results of specific capacity

No.	Well Id	Location		Discharge Q(m ³ /d)	Measured drawdown Sw(m)	Specific capacity from measured data Sc (m ² /d)
		X	Y			
1	PHG1	567688	1338578	4320	4.21	1026.13
2	PHG2	567801	1337977	4320	0.49	8816.33
3	PHG3	568356	1337982	4320	8.74	494.28
4	PHG4	566854	1339244	4320	4.42	977.38
5	PHG5	571398	1335248	4924.8	18.51	266.06
6	PHG6	571821	1334963	5054.4	5.72	883.64
7	PHG7	572289	1334951	4458.24	15.51	287.44
8	PHG8	570553	1334124	4008.96	17.32	231.46
9	PHG9	570089	1333952	4622.4	5.58	828.39
10	PHG10	569560	1334010	5140.8	5.58	921.29
11	THG1	576123	1336656	2764.8	14.74	187.57
12	THG3	575801	1333260	4924.8	13.51	364.53
13	THG4	575471	1331124	5356.8	7.25	738.87
14	Pk2	568476	1341101	6912	14.82	466.40
15	Pk6	569299	1341890	3456	14.45	239.17
16	Pk8	569814	1341065	4320	18.5	233.51
17	Pk9	569485	1341610	4320	5.05	855.45
18	Tk7	569334	1341467	4320	4.69	921.11
19	HG1	568082	1338941	4406.4	20.88	211.03
20	HG2	569450	1338823	4492.8	15.53	289.30
21	HG3	569659	1338130	4492.8	38.1	117.92
22	HG4	569354	1339493	4406.4	15.66	281.38
23	HG5	571782	1333845	4320	14.37	300.63
24	HG6	567804	1339909	4492.8	11.26	399.01
25	HG7	568283	1340339	4320	32.05	134.79
26	HG8	567346	1340010	4320	9.67	446.74
27	HG9	569905	1339618	1036.8	54.8	18.92
28	HG10	570348	1339366	2937.6	37.69	77.94
29	HG11	571055	1335915	4320	20.77	207.99
30	HG12	572295	1335804	4320	14.42	299.58
31	HG13	571683	1336365	4320	13.35	323.60
32	HG14	571067	1336466	4320	12.87	335.66
33	HG15	574997	1330600	4320	11.24	384.34
34	HG16	574865	1331232	2160	35.55	60.76
35	HG17	574673	1331879	4320	16.53	261.34
36	HG18	574474	1332360	4320	17.05	253.37
37	Weremegna	571945	1331680	691.2	2.41	286.80

Appendix 3: Calculation of PET using Hargreaves method

Kobo							
Parameters							
Month	Ta	Tmax (°C)	Tmin (°C)	Td (°C)	Ra	PET (mm/d)	PET (mm/month)
January	19.5	26.2	12.8	13.4	12.8	4.0	124.6
Feb	20.5	28.6	12.4	16.2	13.9	4.9	138.0
March	22.6	29.8	15.4	14.4	14.8	5.2	161.8
April	23.85	30.9	16.8	14.1	15.2	5.5	164.0
May	25.2	33.2	17.2	16.0	15	5.9	184.0
Jun	26.4	34.3	18.5	15.8	14.8	6.0	179.4
July	25.1	32.1	18.1	14.0	14.9	5.5	170.5
August	23.4	30.7	16.1	14.6	15	5.4	168.4
Sep	22.85	30.9	14.8	16.1	14.8	5.6	166.6
Oct	21.3	29.6	13.0	16.6	14.2	5.2	161.3
Nov	20.35	28.4	12.3	16.1	13.1	4.6	138.4
Dec	18.95	26.9	11.0	15.9	12.5	4.2	130.6
Annual PET (mm/year) of the area							1887.5

Maichew							
Parameters							
Month	Ta	Tmax (°C)	Tmin (°C)	Td (°C)	Ra	PET (mm/d)	PET (mm/month)
January	13.7	19.6	7.7	11.9	12.8	3.2	99.0
Feb	14.7	21.2	8.1	13.1	13.9	3.8	116.4
March	16.1	22.1	10.1	12.0	14.8	4.0	123.9
April	17.0	22.8	11.2	11.6	15.2	4.1	128.5
May	18.1	24.3	11.9	12.4	15	4.4	135.2
Jun	19.5	25.4	13.6	11.8	14.8	4.4	135.2
July	17.9	22.7	13.1	9.6	14.9	3.8	117.5
August	17.5	22.2	12.7	9.5	15	3.7	116.2
Sep	16.7	22.6	10.7	11.9	14.8	4.0	125.4
Oct	14.9	21.1	8.6	12.5	14.2	3.8	116.9
Nov	13.8	20.3	7.3	13.0	13.1	3.4	106.4
Dec	13.1	19.4	6.7	12.7	12.5	3.2	98.0
Annual PET (mm/year) of the area							1418.6

Korem							
Parametrs							
Month	Ta	Tmax (°C)	Tmin (°C)	Td (°C)	Ra	PET (mm/d)	PET (mm/month)
January	12.8	19.6	7.7	11.9	12.8	3.1	96.2
Feb	13.0	21.2	8.1	13.1	13.9	3.6	110.6
March	15.0	22.1	10.1	12.0	14.8	3.9	119.7
April	16.0	22.8	11.2	11.6	15.2	4.0	124.8
May	16.7	24.3	11.9	12.4	15	4.2	129.9
Jun	18.0	25.4	13.6	11.8	14.8	4.2	129.8
July	17.6	22.7	13.1	9.6	14.9	3.8	116.5
August	17.1	22.2	12.7	9.5	15	3.7	115.0
Sep	16.0	22.6	10.7	11.9	14.8	4.0	122.9
Oct	14.1	21.1	8.6	12.5	14.2	3.7	114.2
Nov	12.6	20.3	7.3	13.0	13.1	3.3	102.2
Dec	11.9	19.4	6.7	12.7	12.5	3.0	94.3
Annual PET (mm/year) of the area							1376.2

Appendix 4: Chloride concentration of groundwater and rain water

(Valley floor)

No.	Sample index	UTM_X (m)	UTM_Y (m)	Cl _{gw} (mg/l)	P (mm/y)	Cl _p (mg/l)
1	"HG,DW1"	568072	1342974	12.4	739	8.025
2	"HG,RW7"	567338	1327939	30.1	739	8.025
3	"HG,RW8"	567458	1334169	15.2	739	8.025
4	"HG,RW9"			16	739	8.025
5	HG11	571055	1335915	8.64	739	8.025
6	HG12	572295	1335804	8.64	739	8.025
7	HG13	571683	1336365	21.12	739	8.025
8	HG14	571067	1336466	20.2	739	8.025
9	HG 15	574997	1330600	13.9	739	8.025
10	HG 16	574865	1331232	14.89	739	8.025
11	HG 17	574673	1331879	19.86	739	8.025
12	HG 18	574474	1332360	47.7	739	8.025
13	TW1	568755	1329590	26.8	739	8.025
14	TW2	577087	1334495	25.8	739	8.025
15	TW3	579090	1332043	92.3	739	8.025
16	PHG1	567688	1338578	12.9	739	8.025
17	PHG2	567801	1337977	11.33	739	8.025
18	PHG3	568356	1337982	6.18	739	8.025
19	PHG4	566854	1339244	8.24	739	8.025
20	PK1	568066	1340931	10.3	739	8.025
21	PK2	568476	1341101	7.21	739	8.025
22	PK3	568204	1350350	22.66	739	8.025
23	PK4	568000	1353000	14.42	739	8.025
24	PK5	568427	1351843	21.8	739	8.025
25	PK6	569299	1341890	21.63	739	8.025
26	PK7	569892	1341651	15.45	739	8.025
27	PK8	569814	1341065	19.57	739	8.025
28	PK9	569485	1341610	13.39	739	8.025

29	TK1	570278	1354934	26.78	739	8.025
30	TK6	571593	1341396	20.6	739	8.025
31	TK7	569334	1341467	16.48	739	8.025
32	K34	568463	1339475	12	739	8.025
33	K35	573391	1339426	86	739	8.025
34	K37	566652	1338642	14.2	739	8.025
35	K38	568228	1336496	14	739	8.025
36	K40	568020	1335266	13	739	8.025
37	K43	574975	1334515	18	739	8.025
38	K46	574378	1331442	39	739	8.025
39	K47	568097	1327741	45	739	8.025
40	Weremegna	571945	1331680	27.8	739	8.025
41	58	577514	1331428	39	739	8.025
42	59	582500	1331215	57	739	8.025
43	71	579055	1326694	36	739	8.025
44	72	576473	1326267	44	739	8.025
45	72B	576228	1326122	53	739	8.025
46	74	571360	1333546	53	739	8.025
47	57	568124	1327836	53	739	8.025
48	62	574541	1331459	53	739	8.025
49	68	567852	1339683	53	739	8.025
50	51	575598	1339005	90	739	8.025
harmonic mean				18.20		
mean				28.4498		
Geometric mean				22.4352225		

(Western highland)

No.	Sample index	UTM_X (m)	UTM_Y (m)	Cl _{gw} (mg/l)	P (mm/y)	Cl _p (mg/l)
1	"HG,SP1"	577035	1334796	59.9	929	1.82
2	"HG,SP4"			15.6	929	1.82
3	"WG,SP1"	577404	1360915	53.9	929	1.82
4	"WG,SP2"	563009	1355579	23	929	1.82
5	Hormat river			5	929	1.82
7	Kelkel river			5	929	1.82
11	004SP (Tekulesh)	551902	1343764	19.1	929	1.82
12	005SP (Nachaminchi)	567386	1328736	30.4	929	1.82
13	006SP (shebuha)	566959	1328409	36.8	929	1.82
Harmonic mean				13.735		
Mean				27.633		
Geometric mean				20.426		

Appendix 5: Comparative table for hydrochemical analyses

Sample ID	EC	sum of cation(meq/l)	sum of anion(meq/l)	EC/100
51	1584	11.5	15.4	15.8
57	687	4.1	7.3	6.9
58	1023	7.5	12.3	10.2
59	1427	10.3	10.6	14.3
62	963	5.8	10.2	9.6
71	909	5.5	9.7	9.1
72	924	5.5	9.9	9.2
72B	929	5.9	9.7	9.3
74	787	4.9	8.4	7.9
Werem.BH	655	4.7	6.7	6.6
HG3	557	5.6	4.8	5.6
HG5	526	4.0	3.8	5.3
HG6	497	3.5	4.3	5.0
HG7	507	2.8	4.3	5.1
HG8	455	2.5	3.9	4.6
HG9	844	5.2	8.1	8.4
HG11	542	3.9	5.9	5.4
HG12	589	4.3	6.4	5.9
HG13	611	4.3	6.3	6.1
HG14	624	4.2	6.7	6.2
HG15	684	4.5	8.0	6.8
HG16	926	6.0	9.9	9.3
HG17	960	6.6	10.3	9.6
HG18	930	6.5	9.7	9.3
PHG1	446	3.2	5.0	4.5
PHG2	492	3.6	5.9	4.9
PHG3	466	3.3	5.3	4.7
PHG4	458	3.1	5.3	4.6
PK1	503	3.44	5.81	5.03
PK2	517	3.54	5.73	5.17
PK6	674	4.66	8.26	6.74
PK7	656	4.71	7.68	6.56
PK8	584	4.5	6.5	5.8
PK9	661	5.1	7.8	6.6
TK6	470	3.2	5.3	4.7
TK7	627	4.8	7.5	6.3
TW1	684	4.5	6.4	6.8
TW2	828	6.4	8.6	8.3
TW3	1117	6.8	10.5	11.2

Appendix 6: Hydrogeochemistry data

Sample ID	X	Y	Cluster	scheme type	E.N (%)	EC (25 ⁰ c) μ S/cm	pH	TDS	SAR	Water Type	Na	K	Ca	Mg	Cl	SO4	HCO3	F
58	577514	1331428	2	Sp	5	1023	8.11	968.3	1.94	Mg-Na-Ca-HCO3	85	6.2	55	55	39	9	647	0.9
59	582500	1331215	1	Sp	6	1427	7.48	859	8.28	Na-HCO3-SO4	205	10	30	10	57	221	390	5.47
71	579055	1326694	3	Sp	3	909	7.56	805.7	0.84	Ca-Mg-HCO3	38	0.5	78	46	36	23	476	0.29
72	576473	1326267	3	Sp	3	924	7.3	822.17	0.69	Ca-Mg-HCO3	32	0.6	92	44	44	23	447	0.24
72B	576228	1326122	3	Sp	-1	929	7.62	802	0.76	Ca-Mg-HCO3	36	0.6	86	52	53	24	428	0.29
74	571360	1333546	3	Sp	4	787	7.7	698	0.93	Ca-Mg-HCO3	38	3.9	93	21	53	27	388	0.53
57	568124	1327836	4	BH	5	687	7.85	576.7	0.85	Ca-Mg-HCO3-Cl	32	0.7	59	30	53	18	320	0.26
62	574541	1331459	3	BH	6	963	7.64	814.82	1.15	Mg-Ca-Na-HCO3	50	0.7	64	48	53	22	492	0.42
68	567852	1339683	4	BH	10	451	7.85	425.3	0.57	Mg-Ca-HCO3-Cl	19	0.7	39	27	53	10	271	0.25
51	575598	1339005	1	HDW	2	1584	7.52	1306.7	3.31	Na-Ca-HCO3	160	5.2	120	35	90	121	654	1.54
SP004	551902	1343764	4	SP	2.1	739	7.11		0.57	Ca-Mg-HCO3	25.1	0.5	89.6	34.6	19.1	17.0	481.4	0
SP005	567386	1328409	4	SP	-0.57	795	6.96		0.78	Ca-Mg-HCO3	34.4	0.5	88	36.5	30.4	51.2	418.8	0
SP006	566959	1328409	4	SP	-5.13	679	8.06		1.11	Ca-Mg-Na-HCO3	43	0.3	64	29.8	36.8	8.7	339.9	0
HG 3	569659	1338130	4	BH	-24	557	8.02	267	2.20	Mg-Ca-Na-HCO3	77.3	1.3	50.4	23	0.5	3.8	286	0.12
HG 5	571782	1333845	4	BH	-18	526	7.73	252	3.05	Mg-Ca-Na-HCO3	58.6	3.05	30.4	14.9	15	47.2	196	0.43
HG 6	567804	1339909	4	BH	-13	497	7.6	235	0.63	Mg-Ca-HCO3	26.6	1	54.4	22.1	7.5	12.3	242	0
HG 7	568283	1340339	4	BH	-9	507	7.76	243	0.20	Mg-Ca-HCO3	9.09	1.2	52.8	26.4	5.5	11.1	244	0
HG 8	567346	1340010	4	BH	-8	455	7.75	217	0.15	Mg-Ca-HCO3	6.38	0.8	49.6	23.5	7.5	13.8	212	0
HG 9	569905	1339618	3	BH	-2	844	7.18	405	2.73	Mg-Ca-HCO3	41.6	2.7	68	57.1	46.5	47.1	382	0.27
HG11	571055	1335915	4	BH	-5	542	7.68	352	0.84	Mg-Ca-Na-HCO3	31	1.4	46.3	34	8.64	4.4	340.8	0.14
HG12	572295	1335804	4	BH	-3	589	7.72	378	1.06	Mg-Ca-Na-HCO3	39	1.3	40.1	38.3	8.64	4.4	374.7	0.18
HG13	571683	1336365	4	BH	-5	611	7.77	394	0.82	Mg-Ca-Na-HCO3	32	1	52.5	38.9	21.1	22	329.5	0.48
HG14	571067	1336466	4	BH	-2	624	7.76	406	0.74	Mg-Ca-HCO3	29	1.4	56.1	36.7	20.2	16.5	363.4	0.23
HG 15	574997	1330600	3	BH	5	684	7.54	448	0.65	Ca-Mg-HCO3	23	1.2	90.7	29.6	13.9	73	415	0.32
HG 16	574865	1331232	3	BH	-5	926	7.51	520	0.47	Ca-HCO3	24	1.8	168	19.9	14.9	3.59	571	0.32
HG 17	574673	1331879	3	BH	-5	960	7.53	610	0.54	Ca-HCO3	28	1.3	126	46.9	19.9	2.43	590.7	0.38
HG 18	574474	1332360	3	BH	2	930	7.3	630	1.21	Na-Ca-HCO3-SO4	56	1.8	108	32	47.7	119	430.4	0.22

Groundwater Potential evaluation and flow dynamics of Hormat-Golina River catchment, Kobo Valley

PHG1	567688	1338578	4	BH	-2	446	7.56	280	0.65	Ca-Mg-HCO3	22	1	50.2	22.5	12.9	9.11	275.7	0.41
PHG2	567801	1337977	4	BH	-3	492	7.96	322	0.62	Ca-Mg-HCO3	23	0.9	62.2	25.5	11.3	0.38	338.2	0.55
PHG3	568356	1337982	4	BH	-1	466	7.75	304	0.67	Ca-Mg-HCO3	23	0.9	58.8	18.4	6.18	0.29	312.6	0.39
PHG4	566854	1339244	4	BH	5	458	7.08	300	1.02	Mg-Ca-Na-HCO3	31	0.9	33.6	21.9	8.24	1.76	307.4	0.49
PK1	568066	1340931	4	BH	-1	503	7.54	330	0.56	Ca-Mg-HCO3	20.5	1.1	55.4	27.5	10.3	3.62	333.1	0.42
PK2	568476	1341101	4	BH	-2	517	8.48	338	0.60	Mg-Ca-HCO3	22	1.7	42	36.2	7.21	6.4	329.6	1.05
PK6	569299	1341890	4	BH	2	674	7.78	434	0.75	Ca-Mg-HCO3	31.3	1.2	68.9	37.7	21.6	4.47	461.2	0.84
PK7	569892	1341651	4	BH	-1	656	7.52	428	0.86	Ca-Mg-HCO3	35	1.5	67.2	35.7	15.5	1.81	438.1	0.9
PK8	569814	1341065	4	BH	-5	584	7.45	380	0.83	Ca-Mg-Na-HCO3	32	9.4	58.8	33.2	19.6	4.76	358.7	0.46
PK9	569485	1341610	4	BH	-3	661	7.94	432	0.97	Mg-Ca-Na-HCO3	40	2.3	59.6	42.8	13.4	1.05	453.5	0.45
TK6	571593	1341396	4	BH	5	470	7.52	308	1.11	Ca-Mg-Na-HCO3	32.5	8	33.6	18.9	20.6	4.2	281.8	0.62
TK7	569334	1341467	4	BH	-4	627	7.56	410	0.84	Mg-Ca-HCO3	35	1.1	63	41.3	16.5	0.86	427.9	0.84
Weremegna	571945	1331680	3	BH	-5	655	7.76	420	0.96	Ca-Mg-Na-HCO3	38	1.4	81	23.5	27.8	23.7	346.5	0.61
TW1	568755	1329590	3	BH	-7	684	7.49	438	0.74	Ca-HCO3	30	0.9	114	7.3	26.8	17.4	333.1	0.45
TW2	577087	1334495	3	BH	-1	828	7.82	534	2.05	Ca-Na-HCO3	80	1.5	92.8	13.6	25.8	40.9	450.9	0.5
TW3	579090	1332043	3	BH	1	1117	7.29	742	1.27	Ca-Na-Mg-HCO3-Cl	60	1.3	116	31.6	92.3	71.2	435.5	0.5
Kelkel river			4	R	2	314	8		0.4	Ca-Mg-HCO3	15	0	40.4	9.96	5	0	211.1	0
"HG,DW1"	568072	1342974	4	HDW	-0.21	470	7.5		0.55	Ca-Mg-HCO3-CO3	20.7	0	55.5	31.1	12.4	8.6	259.3	
"HG,SP1"	577035	1334796	2	sp	3.54	1070	8.1		1.88	Mg-Na-HCO3	94.3	0	38.3	98.6	59.9	50.9	594.2	
"HG,RW9"			4	HDW	-0.20	450	7.8		0.60	Mg-Ca-HCO3	20.2	0	43.3	26.5	16	7.2	253.2	
"HG,SP4"			4	sp	1.59	450	7.3		0.64	Mg-Ca-HCO3-CO3	25.5	0	54.3	40.5	15.6	8.2	313.6	
K34	568463	1339475	4	BH	0.41	477	7.6		0.89	Ca-Na-Mg-HCO3	27.8	0	54	12.2	12	8	253.8	0.2
K35	573391	1339426	1	BH	0.13	1325	7.6		3.9	Na-Ca-HCO3	166	0	96	24.9	86	40	646.6	0.2
K38	568228	1336496	4	BH	0.56	567	7.3		0.27	Ca-Mg-HCO3	9.4	0	58.4	20.1	14	2	261	0.1
K40	568020	1335266	4	BH	2.14	430	7.5		0.88	Ca-Na-HCO3	25.3	0	50.4	7.6	13	5	206	0.2
K43	574975	1334515	4	BH	0.59	599	7.7		0.3	Ca-Mg-HCO3	10.6	0	60.8	22.1	18	10	266	0.1
K46	574378	1331442	3	BH	-0.1	875	7.4		0.5	Ca-Mg-HCO3	20.7	0	80	31.3	39	20	341.6	0.9
K47	568097	1327741	4	BH	1.18	618	7.6		0.66	Ca-Mg-HCO3-Cl	23.5	0	58.4	23.5	45	15	222	0

Appendix 7: Potential evapotranspiration estimated using Thornthwaite Method

PET for rift floor (Kobo, Waja & Alamata)												
Parameter	Jan.	Fab.	Mar.	Apr.	May	June	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
$T_m (^{\circ}C)$	19.7	20.7	22.3	23.3	24.8	26.0	24.9	23.4	23.0	21.6	20.4	19.3
$T_m/5$	3.93	4.14	4.45	4.663333	4.95	5.19	4.98	4.676667	4.596667	4.313333	4.086667	3.85
$i_m = [T_m/5]^{1.5}$	7.790921	8.423654	9.387285	10.07035	11.01305	11.82364	11.11332	10.11357	9.855179	8.958175	8.261403	7.554245
$I = \sum i_m$	114.3648											
N	11.6	11.8	12	12.3	12.6	12.7	12.6	12.4	12.1	11.8	11.6	11.5
$N_m (N/12)$	0.966667	0.983333	1	1.025	1.05	1.058333	1.05	1.033333	1.008333	0.983333	0.966667	0.958333
T_m/I	0.171819	0.181	0.194553	0.20388	0.216413	0.226905	0.217724	0.204463	0.200965	0.188578	0.178668	0.168321
a =	2.54365357											
$10T_m/I$	1.718186	1.809997	1.945529	2.038797	2.164127	2.269055	2.177243	2.044627	2.009651	1.885778	1.78668	1.68321
$[10T_m/I]^a$	3.962206	4.523176	5.435151	6.122665	7.12596	8.03797	7.236329	6.167292	5.902472	5.020567	4.376429	3.760258
$16N_m$	15.46667	15.73333	16	16.4	16.8	16.93333	16.8	16.53333	16.13333	15.73333	15.46667	15.33333
$16N_m[10T_m/I]^a$	61.28213	71.16464	86.96242	100.4117	119.7161	136.1096	121.5703	101.9659	95.22654	78.99026	67.68876	57.65729
PET_m	1098.764											

PET for Highland (Maichew and Korem)												
Parameter	Jan.	Fab.	Mar.	Apr.	May	June	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
$T_m (^{\circ}C)$	13.2	13.8425	15.5275	16.5	17.4	18.75	17.75	17.275	16.3	14.475	13.1775	12.475
$T_m/5$	2.64	2.7685	3.1055	3.3	3.48	3.75	3.55	3.455	3.26	2.895	2.6355	2.495
$i_m = [T_m/5]^{1.5}$	4.289492	4.606455	5.472645	5.994748	6.491856	7.261844	6.688713	6.422026	5.886083	4.925756	4.27853	3.940994
$I = \sum i_m$	66.25914											
N	11.6	11.8	12	12.3	12.6	12.7	12.6	12.4	12.1	11.8	11.6	11.5
$N_m (N/12)$	0.966667	0.983333	1	1.025	1.05	1.058333	1.05	1.033333	1.008333	0.983333	0.966667	0.958333
T_m/I	0.199218	0.208915	0.234345	0.249022	0.262605	0.28298	0.267888	0.260719	0.246004	0.21846	0.198878	0.188276
a =	1.539513608											
$10T_m/I$	1.992178	2.089146	2.34345	2.490222	2.626053	2.829798	2.678876	2.607187	2.460038	2.184604	1.988782	1.882759
$[10T_m/I]^a$	2.88948	3.108825	3.710205	4.073934	4.421029	4.960023	4.558677	4.372229	3.998161	3.33019	2.881901	2.648807
$16N_m$	15.46667	15.73333	16	16.4	16.8	16.93333	16.8	16.53333	16.13333	15.73333	15.46667	15.33333
$16N_m[10T_m/I]^a$	44.69063	48.91217	59.36329	66.81252	74.27329	83.98973	76.58577	72.28751	64.50366	52.39499	44.57341	40.61504
PET_m	729.002											

Appendix 8: Actual evapotranspiration calculation using Thornthwaite and Mather standard soil water balance model

Appendix 8. 1: AET for deep rooted shrubs, grass land and clay loam texture with a rooting depth of 1m, available water capacity of root zone of 250mm (highland part)

Parameters	Jan.	Fab.	Mar.	Apr.	May	June	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Total
P	27.2	15.8	55.9	83.4	68.4	28.2	182.8	256.0	78.3	52.7	25.2	33.4	907.6
PET	79.9	95.4	106.9	117.0	131.4	135.0	119.1	107.2	101.8	96.5	86.6	82.6	1259.5
P-PET	-52.8	-79.6	-51.0	-33.6	-63.1	-106.8	63.6	148.8	-23.6	-43.8	-61.4	-49.2	-351.9
Acc.pot.WL	-163.4	-243.0	-294.0		-63.1	-169.9					-61.4	-110.6	
Sm	209.55	183.55	181.03	197.61	244.15	195.28	301.44	485.15	498.90	499.20	231.36	224.78	
ΔSm	-15.23	-25.99	-2.53	16.59	46.53	-48.87	106.16	183.71	13.75	0.31	-267.84	-6.58	
AET	42.38	41.79	58.43	117.01	21.82	77.02	119.1	107.2	92.00	52.39	293.04	39.98	1062.19
SMD	37.54	53.63	48.46	0	109.60	57.97	0	0	9.81	44.07	-206.42	42.61	
S	0	0	0	-50	0	0	-43	-35	-37	-44	0	0	0

Appendix 8. 2: AET for moderately rooted cultivated land (cereals and corn) and clay texture with rooting depth of 0.5m, available water capacity root zone of 150mm (the valley and escarpment)

Parameters	Jan.	Fab.	Mar.	Apr.	May	June	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Total
P	50.3	18.0	45.3	67.0	41.0	16.0	146.7	225.0	49.0	34.3	25.0	21.7	739.3
PET	107.7	114.7	156.0	153.5	164.9	165.6	139.6	124.5	116.3	128.4	119.3	105.8	1596.1
P-PET	-57.4	-96.7	-110.6	-86.5	-123.9	-149.6	7.0	100.5	-67.3	-94.0	-94.3	-84.1	-856.8
Acc.pot.WL	-141.45	-238.17	-348.78	-435.33	-559.19	-708.80			-67.25	-161.29	-255.54	-339.64	
Sm	58.42	30.66	14.66	8.24	3.61	1.33	8.36	108.91	95.80	51.18	27.30	15.59	
ΔSm	42.83	-27.76	-15.99	-6.43	-4.63	-2.28	7.03	100.55	-13.10	-44.62	-23.88	-11.72	
AET	7.5	45.8	61.3	73.4	45.6	18.3	139.6	124.5	62.1	79.0	48.9	33.4	739.3
SMD	100.2	69.0	94.6	80.1	119.2	147.3			54.1	49.4	70.4	72.4	
S	0	0	0	0	0	0	0	0	0	0	0	0	

Appendix 8. 3: AET for moderately rooted cultivated land (cereals and corn) and clay texture with rooting depth of 0.8m, available water capacity root zone of 200mm. (highland)

Parameters	Jan.	Fab.	Mar.	Apr.	May	June	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Total
P	27.2	15.8	55.9	83.4	68.4	28.2	182.8	256.0	78.3	52.7	25.2	33.4	907.6
PET	79.9	95.4	106.9	117.0	131.4	135.0	119.1	107.2	101.8	96.5	86.6	82.6	1259.5
P-PET	-52.8	-79.6	-51.0	-33.6	-63.1	-106.8	63.6	148.8	-23.6	-43.8	-61.4	-49.2	-351.9
Acc.pot.WL	-163.4	-243.0	-294.0	0	-63.1	-169.9	0	0	0	0	-61.4	-110.6	
Sm	160.4	135.9	133.6	150.2	194.2	146.9	253.0	436.7	450.5	450.8	181.5	175.1	
Δ Sm	-14.7	-24.5	-2.3	16.6	44.0	-47.3	106.2	183.7	13.7	0.3	-269.3	-6.4	
AET	41.9	40.3	58.2	117.0	41.0	119.4	119.1	107.2	101.8	96.5	294.5	39.8	1176.6
SMD	38.1	55.1	48.7	0.0	90.5	15.6	0	0	0	0.0	-207.8	42.8	
S	0	0	0	0	0	0	-43	-35	-37	0	0	0	

Appendix 9: Meteorological data

Appendix 9. 1: Monthly rainfall data

Monthly rainfall (mm) at kobo station

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1996	79	0	31	75	133	53	147	205	67	18	64	0	872
1997	0	0	43	58	48	52	147	94	37	169	49	0	661
1998	54	32	24	39	12	4	147	312	51	6	0	0	860
1999	316	226	2	12	48	34	147	20	107	25	0	0	790
2000	1	0	2	76	42	5	147	268	49	88	24	83	864
2001	0	0	71	19	16	2	147	220	98	8	4	2	671
2002	5	0	0	0	13	3	147	296	117	16	0	67	612
2003	41	33	35	66	33	11	147	248	42	0	0	43	690
2004	30	0	28	88	3	26	147	162	9	74	36	10	582
2005	8	0	34	158	126	3	147	191	23	9	65	0	742
Mean	53	29.1	27	59.1	47.4	19.3	147	202	60	41.3	24.2	20.5	734.9

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1996	19.7	0	83.2	120.6	166.2	26.3	94.2	195	53.9	15.4	47.5	4.9	826.9
1997	10.2	0	89.8	20	27	3.6	69.7	54.6	6.9	229.6	79.2	0	590.6
1998	76.4	30.8	47.1	27.4	37.7	0	310.6	344.5	92.1	8	0	0	974.6
1999	41.4	0	71.1	35.6	4.1	40	92	324	47	0	1	43	699.2
2000	70	0	0	56.4	18.7	7.1	154.1	258.7	7.2	37.1	30	8	577.3
2001	0	0	67.9	19.9	25.9	23	150.1	197	37	9.8	0	0	530.6
2002	62.7	0	21.8	63.8	0	7	65.5	157.7	55.4	0	0	82	515.9
2003	X	60.9	42.3	92.7	0	7.7	112.9	329.4	50.5	0	1	43	740.4
2004	32.3	43.5	33.3	88	5.9	21.4	50	139.4	24.7	3.7	42.5	8.4	493.1
2005	0	8.1	17.4	133.2	88	6.8	142	168.9	21	1	0	0	586.4
mean	34.74	14.33	47.39	65.76	37.35	14.3	124.11	216.92	39.57	30.46	20.12	18.93	664

Monthly rainfall (mm) at Waja station

Monthly rainfall (mm) at Alamata station

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1996	132.9	0	69.2	123.4	115.2	25	76.5	250	36.3	8	58.2	0	894.7
1997	46.1	0	125.1	26.7	28.5	22	87	54.4	72	191.6	139	0	792.4
1998	179	23.4	25.5	35.2	19.5	0	348	271.9	63.5	17.6	0	0	983.6
1999	44.3	0	20.8	9	7	1	211.4	431.8	66.7	54.5	0	0	846.5
2000	0	0	10	43.5	74	0	246.2	450.1	68.4	14.8	83.3	72.8	1063
2001	0	0	157.9	12.8	29.5	16.8	224.8	244.3	24.8	10	10	2.5	733.4
2002	98.4	0	18	112.3	8	3.5	72.6	213.5	46.1	13.5	0	89.5	675.4
2003	75.8	69.5	41.9	94.2	24.5	12.7	111.8	234.2	22.8	0	0	66.9	754.3
2004	33	16	39.6	168	13.5	49.5	117	243	41.1	8.2	21	20	720.9
2005	21.3	1.4	110.3	131.6	65.8	24	141.5	167	33.1	6	0	0	702
mean	63	11	62	76	39	15	164	256	47	32	31	25	821

Monthly rainfall (mm) at Maichew station

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	annual
1996	8.8	1.2	123.5	146.4	141.2	66.6	117.2	246.5	42.1	4.1	57.3	0	954.9
1997	15.8	0	51.7	59.3	38.4	83.8	166.5	64.2	63.8	206.1	80.8	0	830.4
1998	65.1	33.3	35	39.4	116.5	x	x	214.8	223.5	10.9	0	0	738.5
1999	45.4	0	10.8	22.3	15.9	12.9	176.7	253.5	77.8	109.8	0.4	1.9	727.4
2000	0	0	5.9	17.7	65.1	12	195.8	194.4	126.7	151.3	61.7	74.9	905.5
2001	0	2	92.9	9.2	34.5	26.6	212.2	283.2	83.7	25.3	0	11	780.6
2002	83.7	0	34.3	67.5	40.9	21.6	67.4	188.6	92.9	19.3	0	33.5	649.7
2003	24.4	38.2	93	193.6	13.1	13.7	106.8	321	31.5	4.7	0.3	17.9	858.2
2004	12.7	5.3	19.7	127.3	0.9	59	140.8	247.2	27.4	37.7	3.2	0	681.2
2005	6.4	2.6	51.2	61.4	98	18.1	119.5	219.2	22.7	21.5	29	0	649.6
2006	0	0.1	56.6	80.4	47.5	23.8	179.5	292.2	83.7	64.4	11.3	116.6	956.1
2007	33	41.4	9.6	55.5	7.2	47.8	297.9	212.8	48	9.7	3.8	0	766.7
2008	35.8	0	0	13.5	68.6	28.5	83.9	135.5	101.2	91.7	47.7	0	606.4
Mean	23.27	14.59	46.84	73.82	60.65	29.3	159.53	220.97	72.453	51.359	21.429	22.82	797

Monthly rainfall (mm) at Korem station

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1996	35.9	0.6	98.1	241.8	165.3	67.9	137.1	281.4	63.1	11.4	72.7	0	1175
1997	9.9	2	97.7	50.7	92.9	63.6	172.1	55.9	58.8	322.6	164.1	1.1	1091
1998	159.6	38.5	26.7	27.8	80.2	12.4	397.2	355.8	212.3	45.6	0.2	0	1356
1999	65.8	0	2.8	49.8	12.8	32.1	234.9	350.1	112.2	44.5	2.2	0.4	907.6
2000	0	0	3.5	48.2	76.2	9.3	317.6	321	90.8	133.2	65.6	93.8	1159
2001	1.9	3.2	130.1	22.1	36.1	50.9	282.8	380.1	62.4	13.2	2	13.3	998.1
2002	65.3	0.7	34.1	107	15.6	3	137.2	228.6	90.3	8	0	92.6	782.4
2003	13	24	74.2	74.8	23.7	20.1	168	381.1	77.5	1.8	3.9	30.1	892.2
2004	13.9	6	40.9	55	1.9	54	143.6	249.1	65.5	34.8	21.9	9.9	696.5
2005	8.3	0	106.1	223.4	163.4	28.1	253	297.6	40.6	36.5	0	0	1157
2006	9.9	1	182.2	96.2	44.6	6.9	149	307.4	51.7	60.1	10.2	172.2	1091
Mean	31.29	17.14	65.47	93.07	75.72	26.7	205.51	291.39	84.327	54.193	28.647	44.43	1018

Monthly rainfall (mm) at Muja station

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1996	17	5	124	99	98	46	206	275	68	2	52	9	1001
1997	7	12	94	41	39	96	164	163	21	41	61	13	751
1998	13	0	14	22	68	0	371	273	14	5	0	13	793
1999	15	0	0	31	5	4	313	267	50	26	0	5	715
2000	0	0	9	82	4	0	213	272	36	17	45	21	699
2001	0	0	12	77	24	0	285	310	5	0	0	3	715
2002	37	23	63	15	4	3	196	158	12	0	0	37	548
2003	0	21	38	24	0	80	194	247	31	0	14	0	648
2004	0	20	20	44	0	0	160	208	0	18	0	3	473
2005	0	0	44	56	123	0	257	191	34	0	0	0	704
Mean	9	8	42	49	36	38	236	236	27	11	17	10	705

Appendix 9. 2: Monthly maximum temperatures

Monthly Tmax (⁰C) at Kobo station

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	annual
1996	X	x	x	30.4	30.1	32.1	31.7	30.2	30.4	29.7	27.1	26.1	29.756
1997	25.4	27.9	29.3	30.3	33.1	33.4	32.3	31.8	32.4	27.9	27.2	27.2	29.85
1998	25.4	26.7	29.1	32.4	33.5	36	30.9	28.7	29.9	29.3	28.3	27.6	29.817
1999	26.9	30.4	29	32.2	34.2	35.3	30.5	29.7	x	x	x	x	31.025
2000	X	29.2	30.4	31.3	33	34.7	32.1	30.3	30.5	28.6	27.4	26.1	30.327
2001	25.5	28.1	28.7	X	x	X	x	X	x	x	x	x	27.433
2002	X	x	30	31.6	34.3	33.8	34	30.9	29.9	30.5	29.5	26.4	31.09
2003	25.9	29	30.3	27.6	34	34.6	32.2	X	x	30.3	28.2	26	29.81
2004	27.6	27	30.3	30.8	34.6	34.2	32.7	31.5	31.9	30	29.7	27.1	30.617
2005	26.9	30.2	31.3	31.5	31.7	35	32.7	32.3	31.6	30.8	29.4	28.3	30.975
Mean	26.23	28.56	29.82	30.9	33.17	34.34	32.12	30.68	30.94	29.64	28.35	26.85	30.07

Monthly Tmax (⁰C) at Waja station

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	annual
1996	27.4	31.7	30.3	31.3	31.6	33.1	32.9	31.4	32	31.4	29.1	28.1	30.858
1997	27.6	29.5	29.8	30.6	33.7	33.9	33.1	33.6	34.6	30.3	28.6	29.1	31.2
1998	27.9	29.2	29.8	31.4	33.6	37.4	31.5	29.4	30.3	30.2	29.3	29.1	30.758
1999	27.6	30.5	29.2	32.7	34.4	X	x	X	x	x	x	X	30.88
2000	x	27	27.7	26.8	28.5	29.6	26.6	24.7	24.7	23.3	23.4	X	26.23
2001	20.8	23	23.4	24.6	27.1	X	x	X	x	x	29	29.4	25.329
2002	29.8	29.7	31.7	34	35.3	X	35.3	30.6	33.1	31.3	29.7	28.7	31.745
2003	x	29.9	29.6	31.8	33.9	36.4	34	30.8	31.6	31.5	30	27.9	31.582
2004	28.9	28.9	30.3	X	34.3	34.1	x	31.7	31.6	29.9	29.7	26.8	30.62
2005	28	31.1	31.1	32	31.6	35.9	32.3	31.1	x	x	29.4	27.9	31.04
2006	28.6	30.5	31.6	29.8	33.3	35.5	33.8	31	31.4	31.1	29.6	28.9	31.258
Mean	27.62	29.35	29.68	30.61	32.55	34.67	32.58	30.53	31.27	30.03	29.05	28.41	30.529

Appendix 9. 3: Monthly minimum temperature

Monthly Tmin (⁰C) at Kobo station

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1996	X	X	x	17.3	16.5	17.4	18.2	17.5	15.7	12	11.7	10.2	15.17
1997	13.3	12.3	15.9	16.2	17.7	18.7	18.5	17.8	16.3	15.5	15.6	11.9	15.81
1998	15.4	15.3	17.2	18.1	17.9	20.7	18	17.3	16.1	14.5	10.1	8.4	15.75
1999	11.6	11.1	15.5	16	17.5	18.2	17.3	16.2	x	x	X	X	15.43
2000	X	10.6	14.1	16.5	16.1	15.9	14.9	11.8	7.1	9.4	7.7	7.2	11.94
2001	7.1	7.4	11.6	X	x	X	x	x	x	x	X	X	8.7
2002	X	X	16.2	16.5	16.9	19.3	19.6	17.6	15.6	13	12.1	15.2	16.2
2003	13.5	15	16.4	17	17.6	19.3	19.9	x	x	12.6	13	11.3	15.56
2004	14.7	13.5	15	16.8	16.6	18.3	18.1	13.6	15.5	13.3	16	13.9	15.44
2005	13.9	14.1	17.1	17.2	18.1	18.6	18.7	17.1	17.2	13.4	12.5	9.6	15.63
Mean	12.79	12.41	15.44	16.84	17.21	18.489	18.13	16.113	14.79	12.96	12.34	10.96	14.56

Monthly Tmin (⁰C) at Waja station

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1996	14.4	12.4	16.9	16.2	16	17.3	18.3	17.2	15.2	11.2	10.9	9	14.58
1997	12.8	11.6	15.4	15.6	15.7	17	17	17.5	16	16.1	15.6	12.1	15.2
1998	15.2	14.2	16.7	15.3	15.1	17.7	18.4	17	15.7	13.8	9.5	6.3	14.58
1999	10.3	9.1	14.4	14.4	16.1	X	X	x	x	x	x	X	12.86
2000	X	8.5	11.8	15.5	15.5	16.9	17.5	16.2	15.1	13.1	13.6	X	14.37
2001	10.4	11	11.8	12.2	13	x	X	x	x	x	9	8.4	10.83
2002	11.7	10.4	12.9	17.3	16.6	x	16.2	15.4	12.1	10.3	9.1	8.1	12.74
2003	X	10.1	9.9	9.7	x	15.8	19.3	16.8	15.8	11.3	11.2	10.5	13.04
2004	14	12.6	13.3	X	14.3	17.1	X	20.7	20.6	18	15.6	11.6	15.78
2005	13.4	12.4	16.3	14.8	17	17.2	17.7	17	x	x	10	6	14.18
2006	10	14.1	13.5	14.4	17	16	16.7	15.5	13.8	11.5	10	11.5	13.67
Mean	12.02	11.87	13.95	14.71	15.68	16.811	17.64	17.05	15.5	13.13	11.34	9.65	14.11

Monthly Tmin (⁰C) at Alamata station

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1996		12.9	16	16.4	16.1	16.1	16.7	16.3	15.5	13.9	12.7	11.5	14.92
1997	12.9	12.9	15.8	16.2	17.6	18.6	17.6	17.5	17	15.9	16.2	12.8	15.92
1998	14.9	15	16.6	17.9	18.1	19.9							17.07
1999	12.4	11.9	13.3	17.3	20.2		18.8	16.7	10.2	5.7	3.9	1.9	12.03
2000	2.3	5.3	6.6	7.9	10.1	11.4	11.6	9.2	8.7	7.9	6.5	6.3	7.817
2001	3.9	6.1	8.3	10.1	12.2	13.9	11.8	10.7	10.4	10.8	7.8	6.9	9.408
2002	9.5	14.4	17	17.7	18.6	20	19.7	16.7	16.7	15.9	15.4	16	16.47
2003	14.3	15.7	17.4	18	20.3	20	19.4	17	17.4	15.9	15	12.9	16.94
2004	14.6	8.8	10.1	16.1	18	19.5	18.7	17.8	17.1	15.4	15.2	15.1	15.53
2005	14.4	15.3	17.2	17.7	17.9	19.1	18.9	16.3	16.6	15.6	12	12.1	16.09
2006	14	16.2	15.5	16.4	17.8	19.1	17.6	16.3	16.5	16.5	15.8	15.6	16.44
2007	14.48	16.04	16.5	16.88	18.1	17.917	17.4	16.635	16.12	15.44	15.68	13.59	16.23
Mean	12.25	13.05	14.63	16.01	17.04	17.608	17.06	15.553	14.69	13.73	12.7	11.75	14.67

Monthly Tmin (⁰C) at Maichew station

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1996	8.5	8.4	10.6	11.2	11.2	13.1	11.7	12.7	10.2	7.7	7.4	6.3	9.917
1997	8	6.9	10.5	10.6	11.5	13.3	13.4	12.4	10.5	10.4	10.3	7	10.4
1998	9.7	9.2	10.6	12	13.3	13	x	x	x	7.3	5.2	4.5	9.422
1999	6.5	6.9	9.1	9.9	12	12.7	9.7	11	10.3	9.3	5.3	5.9	9.05
2000	6.1	6.3	8.1	10.6	11.7	13.7	13.5	12.4	10.2	8.6	7.7	6.8	9.642
2001	5.7	6.1	10.3	9.9	11.8	13.3	12.8	13.9	11.7	9.1	5.8	6	9.7
2002	8.1	7.7	10.4	10.7	11.4	14.3	14.8	12.6	9.5	8.1	7.3	9	10.33
2003	7.8	9.2	10.4	11.5	11.1	13.4	13.4	12.7	11.6	7.9	7.1	6.3	10.2
2004	10.7	7.8	8.9	11.5	11.8	13.5	13.6	13.1	10.2	8.4	7.4	7.9	10.4
2005	7.9	8.7	10.7	11.6	12.5	13.8	13.7	13.1	11.6	7.8	7.3	4.7	10.28
2006	7	9.2	10.6	11.5	12.2	14	13.6	12.8	10.4	9.2	7.5	9.2	10.6
2007	8.3	9.5	9.5	11.2		14.3	12.9	12.2	11.5	8	7	4.6	9.909
Mean	7.707	8.114	10.13	11.15	11.93	13.594	13.14	12.7	10.74	8.556	7.269	6.719	10.15

Monthly Tmin (⁰C) at Korem station

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1996	8.5	6.6	9.6	10.2	5.4	8.5	12.2	12	9.2	4.1	4.5	4.1	7.908
1997	5.7	5.7	9.3	8.7	8.7	11.3	12.5	11.5	7.1	8.7	10	4.2	8.617
1998	8.5	7.5	9.3	9.3	10.2	9.8	12	11.8	9.6	6.9	1.1	-0.7	7.942
1999	3.4	1.7	6.5	7.4	8.6	9.7	11.6	10.7	8.4	6.8	0.4	2.3	6.458
2000	2.5	1.7	5.6	9.4	8.9	10.8	12.3	11.5	8.5	6.8	5.3	4.4	7.308
2001	3.3	3.3	8.5	7.2	9.2	11.8	12.3	11.9	8.2	6.8	2.5	2	7.25
2002	6.3	4.5	8.3	8.6	7.2	11	11.8	11.1	8.3	4.5	3	7.2	7.65
2003	X	2.5	3.9	10.1	9.8	11.2	13.1	12	9.9	4.1	4.5	2.8	7.627
2004	6.7	5.8	7.4	X	7.8	11.3	X	12.1	8	6	5	6.2	7.63
2005	7.3	5.4	9.7	9.8	10.5	10.4	11.9	11.8	9.9	5.1	3.8	4.2	8.317
Mean	5.8	4.47	7.81	8.967	8.63	10.58	12.19	11.64	8.71	5.98	4.01	3.67	7.671

Appendix 9. 4: Monthly relative humidity (RH) (%)

Monthly relative humidity (%) at Kobo station at 1800

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1996				46.9	56.3	49.1	53.3	56.8	52.3	43	48.4	45.8	50.2
1997	64.5	34.4	43.3										47.4
1998				35.4	30.7	27	52.4	63.8	58.9	47.2	33.3	42.9	43.5
1999	56.2	56.9											56.5
2000													
2001													
2002						20.8	32.9	50	55.1	38.4	32.8	58.7	41.2
2003													
2004	56	42.3	32.9	48.9	21.9	24.2	44	55.1	45.5	42.7	36.7	50.6	41.7
mean	58.9	44.53	38.1	43.73	36.3	30.28	45.65	56.43	52.95	42.83	37.8	49.5	46.75

Monthly relative humidity (%) at Kobo station at 1200

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1996		44		47.2	56.5	48.6	44.7	50.4	43.8	35.8	35	47	45.3
1997	58.1	44	37.6										46.6
1998		44		39.5	33.6	24.3	51.5	60.3	49.7	39.5	35	47	42.44
1999	56.6	44									35	47	45.65
2000													
2001													
2002		44				21.1	29.5	42.6	51.1	30.8	35	47	37.638
2003													
2004	49.8	44	32.6	42.9	22.2	26.4	32.8	44.2	40.8	36.4	35	47	37.842
2005	51.1	37.3	43	39.4	44.3	25.8	41.2	43.6	42.1	36.6	39	32.5	39.658
mean	53.9	43.04	37.7	42.25	39.15	29.24	39.94	48.22	45.5	35.82	35.7	44.6	41.254

Monthly relative humidity (%) at Kobo station at 600

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1996	87			75	86.1	53	72.2	84.8	89.1	82.5	79.2	81.2	79.01
1997	88	74.1	83.4	75		53							74.7
1998	87			75	60	53	77	90	93.1	83.3	72.4	76.7	76.75
1999	87	83.1		75		53							74.525
2000													
2001													
2002	87			75		53	66.2	82.4	89.5	78.3	72	87.1	76.722
2003													
2004	87	82.6	66.8	75	50.7	53	66.1	79.4	81.8	80.5	75.9	84	73.567
2005	84.8	70.3	78.4	72.7	84.7	59	71.6	80.8	83.7	77.1	75.2	74.1	76.033
mean	86.83	77.53	76.2	74.67	70.38	53.86	70.62	83.48	87.44	80.34	74.9	80.6	76.408

Monthly relative humidity (%) at Maichew station at 1800

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1996	76	53	69	62	58	49	59	68	53	45	57	56	58.75
1997	73	50	69	56	42	45	62	54	44	63	73	63	57.833
1998	85	77	69	47	57	32		74	67	58	45	42	59.364
1999	58	34	60	35	28	27	67	65	63	69	47	54	50.583
2000	49	35	38	40	36	29	67	71	59	70	69	66	52.417
2001	68	52	69	45	47	47	67	72	64	59	50	53	57.75
2002	78	55	60	50	36	36	44	62	59	46	45	76	53.917
2003	68	60	59	55	34	37			59	43	52	62	52.9
2004	72	54	46	67	29	40	54	64	49	51	52	62	53.333
mean	69.67	52.22	59.9	50.78	40.78	38	60	66.25	57.44	56	54.4	59.3	55.4

Monthly relative humidity (%) at Maichew station at 1200

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1996	62	44	56	53	54	45	56	52	41	38	45	46	49.333
1997	59	38	53	49	38	40	60	50	38	55	63	51	49.5
1998	68	63	54	43	54	37		67	58	49	36	32	51
1999	48	28	44	30	28	24	62	64	52	56	37	46	43.25
2000	36	28	33	36	33	29	59	67	51	58	58	57	45.417
2001	55	43	62	41	37	42	62	67	53	48	43	41	49.5
2002	64	44	51	42	29	33	42	55	50	40	40	63	46.083
2003	53	45	49	49	32	34			46	42	44	49	44.3
2004	51	43	39	55	25	34	51	63	45	44	45	53	45.667
mean	55.11	41.78	49	44.22	36.67	35.33	56	60.63	48.22	47.78	45.7	48.7	47.422

Monthly relative humidity (%) at Maichew station at 600

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1996	86	74	86	83	83	59	68	71	72	80	77	73	76
1997	73	69	77	76	74	68	67	71	79	87	94	84	76.583
1998	87	77	78	72	75	48		72	72	83	76	58	72.545
1999	72	50	64	67	58	44	69	73	84	91	82	83	69.75
2000	69	55	66	60	60	49	67	74	82	94	83	83	70.167

2001	80	65	72	79	73	61	73	79	84	86	86	76	76.167
2002	86	70	78	76	58	49	66	70	82	86	80	89	74.167
2003	73	69	79	78	68	74			59	82	78	62	72.2
2004	73	70	64	86	47	53	64	70	81	84	83	83	71.5
mean	77.67	66.56	73.8	75.22	66.22	56.11	67.71	72.5	77.22	85.89	82.1	76.8	73.147

Appendix 9. 5: Mean monthly sunshine hours

Mean monthly sunshine hours at kobo station

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1996	6.8	5.3	7.9	9.6	9.9	8.5	4	5.1	6.8	9.6	9.9	8.8	7.6833
1997	8	7.3	9.3	6.9	9.4	6.2	3.1	5.1	7.3	9.5	9.7	8.1	7.4917
1998	6.3	7.5	8.9	9.5	9.2	6.8	6.7	7.4	6	7.1	9	7	7.6167
1999	6.9	4.4	8.7	6.6	9.1	6.3	6.1	6.5	7	9.6	10.1	9.3	7.55
2000	9.3	7.2	6.1	7.6	9.1	5.1	5.2	5.1	5.1	8.2	9.3	8.7	7.1667
2001	8	7.4	8.9	7.9	9.8	8.3	3.4	6.6	7.1	7.9	8.1	7.9	7.6083
2002	7.8	8.6	8.7	9.7	6.5	5.7	4	5.8	7.7	8.9	9.1	8.5	7.5833
2003	8.7	10.2	8.1	9	6.8	6.4	8.3	7.1	6.7	7.3	8.6	9	8.0167
2004	8.1	8.7	9	6.8	7.2	6.1	7.3	5.6	6.2	8.1	9.9	9.4	7.7
mean	7.77	7.4	8.4	8.18	8.56	6.6	5.34	6.03	6.66	8.47	9.3	8.52	7.6019

Mean monthly sunshine hours at Maichew station

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1996	7.4	7.5	6.4	7.7	7.8	7.6	5.8	5.7	7.2	6.6	7.1	7.4	7.0167
1997	7.9	8.8	5.5	7.2	8.2	6.2	5.5	6.2	6.7	6.2	6.6	8.4	6.95
1998	5.2	6.3	7.4	8.7	8.7	6.9	4.2	4.3	7.3	8.5	9	9.3	7.15
1999	7.4	9.8	7.2	10.2	9.7	7.3	3.9	4.9	7	6	8.9	7.7	7.5
2000	9	9.8	9.7	7.3	9.2	6.3	5.2	5.5	5.9	7.1	7.8	6.3	7.425
2001	9	7.9	4.4	6.2	7.2	12.1	4.6	5	7	7.9	6.9	8.3	7.2083
2002	8.2	8.2	7.6	9.4	9.3	6.3	6.1	6.3	6.7	7.8	7.7	6.7	7.525
2003	6.4	8	6.3	9.9	9	6	4.7	4.4	7.3	9.4	8	7.9	7.275
2004	6.9	8	8.6	7.6	10.5	5.9	5.2	5.4	6.3	8	8.3	7.4	7.3417
2005	6.5	8.6	7.5	8.3	8	8.4	5.1	5.7	6.9	8.2	7.7	9.5	7.5333
2006	5.3	7.8	7.3	7.7	8.7	5.8	4.5	5.2	7	7.1	7.7	5.3	6.6167
2007	5.7	6.8	8.3	7.8	9.2	5.6	4.7	6.3	7	8.4	7.9	8.8	7.2083
mean	7.08	8.13	7.18	8.17	8.79	7.03	4.96	5.41	6.86	7.6	7.8	7.75	7.2292

Appendix 9. 6: Mean monthly wind speed (m/s) at 2m height

Mean monthly wind speed (ms-1) at Maichew station at 2m height

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1996	1.1	1.3	1.3	1.3	1.3	2.9	3.8	2.7	1.2	1.2	1.2	1.2	1.7083
1997	1.1	1.3	1.3	1.3	1.5	1.9	3.1	2	1.3	1.2	1	1	1.5
1998	0.9	1	1.2	1.4	1.4	1.9	3.6	2.6	1.2	1.2	1.3	1.3	1.5833
1999	1.2	1.4	1.4	1.5	1.6	2	3.3	2.2	1.1	0.9	1.1	1.1	1.5667
2000	1.2	1.3	1.3	1.4	1.4	2.2	3.4	2.8	1.1	0.9	0.9	1	1.575
2001	1.2	1.3	1.3	1	1.2	2.4	3.2	2.5	1.1	1.2	1.1	1.1	1.55
2002	0.9	1.2	1.2	1.3	1.3	2.4	2.5	2.5	1.1	1.2	1.2	1.1	1.4917
2003	1.1	1.3	1.3	1.3	1.3	1.8	3.4	2.7	1.4	1.2	1.2	1.1	1.5917
2004	1.2	1.3	1.3	1.2	1.6	1.9	3.2	2.3	1.2	1.2	1.2	1.2	1.5667
2005	1.1	1.2	1.3	1.4	1.3	3	3	2.7	1.2	1.2	0.9	1	1.6083
mean	1.1	1.26	1.29	1.31	1.39	2.24	3.25	2.5	1.19	1.14	1.11	1.11	1.5742

DECLARATION

I, the undersigned, declare that this thesis is my original work and has not been presented for a degree in any university and that all sources of materials used for the thesis have been duly acknowledged.

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The thesis has been submitted for examination with my approval as university advisor.

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