ADDIS ABABA UNIVERSITY

COLLEGE OF NATURAL SCIENCES, SCHOOL OF EARTH AND PLANETARY SCIENCES, DEPARTMENT OF EARTH SCIENCES

SUSTAINABLE GROUNDWATER DEVELOPMENT AND MANAGEMENT FOR IRRIGATION IN RAYA AND KOBO VALLEYS, NORTHERN ETHIOPIA

A thesis submitted to the school of graduate studies of Addis Ababa University

In partial fulfillment of the requirements for the degree of Masters of Science in Hydrogeology

By

Abdella Abdu

April, 2011

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ABDELLA ABDU

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

Approved by the Board of Examiners

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Disclaimer

This document describes work undertaken as part of a Hydrogeological master degree program at the Addis Ababa University, Department of Earth sciences. All views and opinions expressed therein remains the sole responsibility of the author, and don't necessarily represent those of the institute.

Dedicated to

My family with love and Gratitude

Abstract

The study focuses on the sustainability of the groundwater use for domestic and agricultural purpose in Raya and Kobo valleys. The Raya valley, which comprises of Alamata, Raya-Azebo, Enda-Mehoni, Ofla weredas is found in southern Tigray regional state bounded within in $12^{\circ} 5'$-$12^{\circ} 58'$ north latitude and $39^{\circ} 20'$ -$39^{\circ} 53'$ east longitude. The Kobo valley, which comprises of Kobo wereda, is found in northern Wello of Amhara regional state bounded with in $11^{\circ} 5'$ -$12^{\circ} 11'$ north latitude and $39^{\circ} 22'$ -$39^{\circ} 48'$ east longitude. The study areas are endowed with groundwater fertile land livestock and agro-climatic conditions.

The sustainability of the groundwater use for domestic and agricultural purpose is evaluated using indicators of groundwater importance (total groundwater abstraction / total renewable groundwater resource), indicators of groundwater exploitation and groundwater vulnerability indicator. To estimate the value of these indicators, the annual recharge is estimated using water balance method and chloride mass balance method. The total annual recharge estimated, for Raya valley and Kobo valley, based on the former method is 129.9MCM and 85.59MCM, respectively. Further, using the latter method it was estimated that 52.48mm/year for Raya valley and 52.8mm/year for Kobo valley. Moreover, the total groundwater abstraction is estimated by computing the crops irrigation requirement using CROPWAT 8 software and per capita demand (20l/day) of the inhabitants that live in the valley. Water table fluctuation, which is used in the computation of exploitable groundwater resource, is estimated using cumulative rainfall departure method.

In conclusion, the current groundwater use (development) in the two valleys is sustainable and it is at the stage of under exploitation. In Raya valley, when the intended / proposed pressurized irrigation practice, which covers (26,100ha) using groundwater, is implemented, the groundwater development will be reached unsustainable and moderately exploitable stage. The groundwater quality of the western part of the valleys area is moderately vulnerable whereas the central and eastern parts of the valleys are vulnerable.

At the end, the current groundwater use for domestic and agricultural purpose should be enhanced. But, when the intended/proposed agricultural practice reaches at maximum production in Raya valley, additional recharge must be implemented. To minimize the groundwater vulnerability, proper waste disposal site must be constructed, Continuous groundwater quality assessments must be carried out, when fertilizer(s) is/are applied for the farmland and vulnerability map of the areas should be prepared.

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For every thing, the precious honor goes to Almighty Allah.

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List of Acronym and Abbreviations

CMB chloride mass balance

CRD cumulative rainfall departure

CO-SAERAR Commission for Sustainable Agriculture and Environmental Rehabilitation in Amhara Region

DEM digital elevation model

DWL dynamic water table

EGR exploitable groundwater resource

GWDM groundwater development and management

ITCZ inter –tropical convergence zone

KVDP Kobo valley development project

m.a.s.l meter above sea level

MAR mean annual rainfall

MARH mean annual relative humidity

MASSD mean annual sunshine duration

MAWS mean annual wind speed

MCM million cubic meters

MMR mean monthly rainfall

MMRH mean monthly relative humidity

MoWR ministry of water resource

MSSD monthly sunshine duration

MTS meteorological stations

MWS monthly wind speed

PAHC population and housing cencus

PD primary data

REST relief society of Tigray

RGWR renewable groundwater resource

RVDP Raya valley development project

TGWA total groundwater abstraction

SI sustainability indicators

SWL static water table

WTF water table fluctuation

WWDSE water works design and supervision enterprise

VI vulnerability indicator

CHAPTER ONE

INTRODUCTION

1.1 Background

Groundwater plays an important role in Ethiopia as an important source of water for domestic, industrial and /or agriculture uses. In rural areas, which cover more than 85% of the population of Ethiopia, the problem of water shortage can be solved by proper development and utilization of groundwater. The rural communities should use groundwater for their demand because of its several inherent qualities; widespread and continuous availability, excellent natural quality, draught reliability. It is an important and dependable source of water supply in all climatic regions including both urban and rural areas of developed and developing countries (Todd, 2005). Though groundwater is dependable resource, the sustainability of groundwater use is crucial. To ensure the sustainable utilization of the resource and to give proper solution for water supply problems in arid and semi arid areas, the first attempt should be identification of the main aquifers, which are located in different geological environments and variable climates. Next to groundwater identification, proper development and utilization of the resource is the most important aspect that should be given a great deal of consideration. Parallel to population growth, food demand of people and consequently, the water demand of all sectors are also increasing, agricultural yield and productivity should be increased to provide a sustainable development and food security of the increasing population. That brings the need for effective and sustainable water resource utilization and countries to implement water saving technologies in irrigation practices (Cakmak et al., 2006).

Groundwater use in Ethiopia has been limited to community water supply using shallow and dug wells and unprotected springs. The use of the deep groundwater from boreholes for agriculture is almost non –existent (Tameru Alemyehu, 2006). However, at present the Federal Government of Ethiopia together with the Regional Government is trying to utilize the resource for irrigation purpose at different location of the country. When the groundwater is used for irrigation, it is necessary to maintain the groundwater reservoir in state of dynamic equilibrium over a period of time and the water level fluctuations have to be kept within a particular range over the monsoon and non –monsoon seasons.

1.2 Groundwater Management and Development concept

Though groundwater is a strategic resource due to its usually high quality and availability, the resources is degraded in the long term by over pumping and pollution, and the local and regional utilization of ground water is impaired or even has to be abandoned. Moreover, groundwater management all over the world often lacks sustainability as evidenced by falling water tables, drying wetlands and general deterioration of water quality. As groundwater cannot be renewed artificially on a large scale, sustainable management of this resource is vital. Main objective of sustainable groundwater development and management is to ensure quantity, quality, safety and sustainability of groundwater, which is used as a: strategic source for life (for drinking and other sanitary purposes) and economic development (agriculture, industry) and an important component of ecosystem (Groundwater indicators working group, 2007)

Water resources management encompasses seven major water related activities namely assessment, planning, development, allocation, conservation, protection and monitoring. Grigg (1985) defined water resources management as people's control over water as it passes through its natural cycle, with balanced attention to maximizing economic, social and environmental benefits.

The assessment of water resources entails the quantification of water resources as well as the determination of the suitability of the water, in terms of its quality, for various uses.
Water resources planning involve setting modalities for a systematic and sustainable development of water resources with a view to averting the depletion and degradation of the resource. Water resources planning is sets of possible goals which comprises of assembling needed information and consequences of alternative courses of action for attainment of such goals; displaying the information and consequences of alternative actions in an authoritative manner; devising detailed procedures for carrying out the actions, and; recommending courses of action as an aid to decision makers in deciding a set of goals and courses of action. It is at the planning stage that the use to which water will be put after development is determined and optimized i.e. whether the water resources will be developed to cater for domestic needs, irrigation, hydropower generation, navigation or recreation, etc. At the planning stage the involvement of stakeholders is important.

Stakeholder involvement in all phases of the project cycle i.e. from inception to operation and maintenance, removes communication breakdown and its inherent problems between the beneficiary community on one hand and government officials on the other.

A decision made on the management of water resources without the participation of stakeholders is a recipe for disaster as the program runs the risk of failure. This may arise from the fact that the project may be implemented on the basis of inadequate information or the project may be misunderstood by the community. Involvement of stakeholders in water resources management increases the community's sense of "ownership", enhances decision making, increases efficiency and reduces the need for enforcement. Harmonization of different policies such as Environmental Management Policy, the Forestry Policy, the Wildlife Policy, the Agricultural and Irrigation Policy, and the Water Policy also plays a great role in groundwater management.

Allocation of water resources deals with the distribution of the available water resources to the various sectors in accordance with set regulations. Conservation and protection of water resources aim at safeguarding the resource from depletion and deterioration. The depletion and degradation of water resources may be caused by several factors including deforestation which results in reduced base flows, encroachment upon catchments areas by human settlements and agricultural production activities which accelerate sedimentation problems in reservoirs and river channels, excessive use of agrochemicals and uncontrolled waste disposal which cause water pollution, etc.

Water resources monitoring is a process whereby the availability and quality of water resources is observed over a predetermined time interval. This may involve measuring discharge in rivers; recording lake levels; observing fluctuations in groundwater levels using autographic recorders installed on wells; measuring water quality parameters to determine the suitability of the water for the intended use; installation of sediment traps for use in measuring the rate of sedimentation in rivers and reservoirs; measuring climatic variables such as; temperature, rainfall, wind speed, solar radiation, humidity; etc. This process is important as it enables water resources managers to make informed decisions on what corrective measures are to be implemented, if the quantity and quality of water resources exceeds or falls short of the recommended limits. Groundwater development is an activity which includes assessment, exploitation and management of the groundwater.

1.3 Statement of the problem

Raya and Kobo valleys are rich in land resources for agriculture development. Their low land areas experience low and erratic rainfall distribution, which often fail to satisfy the moisture condition for growing crops. As a result of low rainfall, the area has been affected by drought and poverty. But the need of agricultural development in the area by using groundwater is growing continuously. Many wells were dug and groundwater is being used as source of water for irrigation. However, there is no controlling or managing mechanism of the groundwater reserves. Moreover, due to the expansion of irrigated agriculture there is excessive withdrawal of groundwater. The excessive usage of groundwater may end up with: the water table lowering which increases the cost of pumping and mining of groundwater. For example, the groundwater of the Shire and Mekele has declined beyond the reach. The decreased water tables in these areas caused sever shortage of water for domestic and agricultural water supply (Getachew Welamo, 2009). Thus, to eradicate the problem before occurring in the study area to be able to develop, utilize and manage the groundwater resource, it is necessary to assess the current rate of recharge and extraction.

1.4 Significance of the study

Agricultural production requires water as input. The water should be in proper quantity and of adequate quality. When the quantity of water is unable to satisfy the soil moisture, plants/crops will die. Excessive water use will create water logging and salt will accumulate at the surface and plants will not be productive.

Since groundwater is developed and used for irrigation purpose in the study areas, the utilization of the resource should consider the total amount of groundwater available in the area without affecting the ecosystems which depend on the shallow water table. For the sustainable utilization of groundwater, it is very important to evaluate and mange the productivity of the aquifers along with the consumption of the users for their intended demand. The evaluation and management of the resource requires detailed understanding of the characteristics of the aquifer parameters, the rate of the groundwater recharge and the amount of abstraction. If the nature of the parameters, the rate of recharge and the total amount of withdrawal are known as much as possible, managing the resource will be much easier. This study will provide the following benefits:

- The communities and administrators will have a clear understanding about the available exploitable amount of groundwater.
- Abstraction of groundwater will be managed without affecting the safe yield of the aquifers.
- Water shade of the study areas will be managed in order to manage the groundwater recharge.

The beneficiaries of this study are: Governmental and none- governmental organizations which are involved in agricultural practices and groundwater development, the communities of the areas, investors who want to invest in agricultural activities using groundwater recourse and urban development bureaus of the study areas.

1.5 Research Questions:

1. Where is the groundwater available in the study areas?
2. What is the rate of groundwater recharge of the areas?
3. What is the crop water consumption and domestic water demand? Is the groundwater resource sustainable upon abstraction for domestic and irrigation purpose?
4. Will the current withdrawal rate of groundwater affect the safe yield of the aquifers?
5. If the groundwater level decline upon abstraction, what kind of artificial recharge can be implemented in the study areas?
6. What is the exploitable groundwater resource?
7. What is the safe yield of the groundwater reserve?

1.6 Objective

The primary objective of the study is to asses the groundwater potential and to assesses its sustainability for irrigation and domestic water supply.

The specific objectives include:

- To evaluate and estimated the groundwater table fluctuations in the study areas
- To quantify the amount of the recharge of the precipitation
- To asses the current and future water demand of the area for management purpose.
- To estimated the exploitable groundwater resource and the safe yield of the aquifers of the study area
- To asses the degree of vulnerability of the groundwater.

1.7 Scope of the study

The study covers Alamata wereda and Raya Azebo weredas of the Raya valley. Moreover, the study includes the Kobo /Town/ Wereda, which is found in the Kobo valley. The study focuses on these Weredas because these are the major consumers of the groundwater of the sedimentary deposit found in the valley graben.

Water resources management encompasses seven major water related activities namely assessment, planning, development, allocation, conservation, protection and monitoring. However, the study addresses the sustainability of the groundwater considering the groundwater abstraction for the domestic water supply and irrigation requirements for crops that grow in the area and have crop coefficients. The crops that are proposed by the Ministry of Water Resource (current name, Ministry of Water and Energy) are used in this study to estimate their irrigation requirements. But, for Kobo area coffee and cotton are not included in the present study.

1.8 Literature review

WWDSE and CECP (2006), describes the availability of groundwater and presence of investors who use groundwater for irrigation purpose. But the report doesn't show: total amount of land, the types of crops that grow using groundwater resource in the study area, recharge amount, water consumption of the crops, which are mentioned in the report, how much hectare they cover and safe yield of the reservoir. Moreover , the WWDSE and CECP(2008), states the pump test performed in the Raya area using one pumping and five observation wells which reveals that the average transmissivity of the Mehoni and Alamata sub-basins are 1787, 545, 1435, 2304 m^2 / day , respectively.

REST (1996), which covers the Alamata wereda, the Raya Azebo wereda, Endamahoni wereda and part of Wofla wereda, states that the river system of the Raya basin flows from the mountains to the low land of the plain. The Sulula River, which is found in the Humo shet, drains the excessive water of the Raya basin to the Danakil basin during the rainy season only. Some disappear in the plain by percolation as a result of the absence of definite river course, permeability of the plain and less flow velocity, which gives sufficient time for percolation when there is no high flood.The report also states that the groundwater recharge of the valley is estimated to about 100Mm^3 /year and the groundwater reserve is about 4233Mm^3.The exploitable groundwater reservoir is 110Mm^3/year. The depth of the groundwater is variable: in the south it is 20-40 m variable, in the north it varies above 60m and in the central part of the valley it is 20-60m variable. The flow direction of the groundwater is from west to east at gradient ranging of 0.01-0.02.

Afework Hailu., 2010) which focuses on quantitative characterization of the hydraulic parameters of the Raya valley, describes the main recharge of the valley through the adjacent uplands of the western margin where there exists high precipitation than the low lying areas of the valley. The researcher stated that qualitative determination of hydraulic parameters such as discharge, drawdown and specific capacity of aquifers is one of the important steps in groundwater important .But identification of the safe yield of aquifers, the source of recharge and the total amount abstraction based on the demand and purpose are the most crucial part of groundwater management for its sustainability.

Getachew Welamo (2009), states that groundwater recharge to the Alamata sub- basin is mainly from precipitation and groundwater inflow from the upper sub-basin of Mehoni sub-basin, which is part of Raya valley. The outflow from the groundwater system of the sub-basin includes well withdrawal and sub-surface outflow.

The model of the research was simulated at four scenarios using three wells to study the response of the system. The first scenario was increasing of the current withdrawal by 25% and 50%. The second scenario was decreasing the recharge by 25% and 50%. The minimum and maximum groundwater level change was observed at three different well locations. When the withdrawal was increased by 25%, the groundwater level of the system declined by 3.747m at well OB_4 (N= 1360890, E= 577138) and by 7.74m at well PZ_3 (N=1377425, E=569257). Again an increase of withdrawal by 50% the minimum and the maximum water level decline at wells OB4 and PZ_3 are 7.985m, 31.472m ,respectively. The second scenario of the simulation was by decreasing the recharge by the percentage mentioned above and the effect was observed at well BH_{21} (N= 1361697, E=574000) and PZ_3.When the recharge was reduced by 25%, the minimum water level decline observed at well BH_{21} was 20.333m where as the maximum water level decline was 32.485m. On the other way, reduction of recharge by 50% resulted with a complete drying of well PZ_3.

According to Mohammedsultan Abdella, (2010), the groundwater recharge in the Raya valley is controlled by: climate, geomorphology and geology. The recharge takes place in the hills, where much runoff is created and infiltration occurs along the slope areas, located on the western and eastern parts of the area. Due to the presence of alluvial fans with coarse grained sands, enhanced high infiltration rate occurs in the hill side of the area. The simulated model of this research, which is not verified and used 34 irrigation wells with different discharge rate, indicates the water level decline ranges from 22m to 50m.

Halefom Shiferaw (2006), states that the thickness of the aquifers of the Alamata sub basin become shallower and shallower towards the western and eastern flank where as they get maximum thickness at center of the valley. According to the researcher, the annual groundwater recharge to the Alamata sub basin due to direct precipitation is estimated at $31Mm^3$ taking the area of the plain as 402 Km^2.

Dessie Nedaw (2003) mentioned that some of the streams that flow towards Raya valley floor are perennial on the highlands but when they reach to the valley floor, they diaper in the unconsolidated materials. The approximated annual runoff is 176mm, which flow from the western escarpment to the floor of the valley. The total volume of water that possibly leaves the basin annually as surface runoff is about 60MCM. The researcher also mentioned that the runoff coefficient of the mountains area ranges from 0.13 to 0.22 to estimate the annual run off for the dam proposed by REST, (1998).

Samuel Barnie (2010) who had made a research on hydrogeological and hydro-chemical framework of groundwater for irrigation in the Alankwidi sub basin of the white Volta basin aiming at investigating the groundwater potential for irrigation within the study area stated that hydraulic conductivity (K) and porosity, which is important in the estimation of groundwater potential, was estimated by particle size analysis of sediments of interest. The groundwater potential of the study area was determined from the relation: $GW_p = AxLx\ n$ Where A= average cross-sectional area of the study area (m^2), L= longitudinal length across study area (m^2) which is the length between the topmost and down most ends of the study area and approximately perpendicular to the cross-sectional profile and n = porosity (%).

According to MoWR (2008), the surface water resources in the project area mainly depends on intermittent streams and perennial rivers which originate from the highlands. The streams are characterized by lower dry season flow and flash floods during the rainy season. There are also a number of small springs in the southern part of the project area which flow through out the year and used for traditional irrigation schemes. The dry season flow of most of the streams is totally abstracted by farmers for small traditional irrigation schemes far upstream of the proposed irrigable areas. So it is not of direct interest for this envisaged irrigation project. The Raya valley is drained by a number of streams. The annual total surface water resources generated from the upland catchments is estimated at about 114 million cubic meter.

(Abrham Melesse, 2009), states the main crops grown in the area before the KGVDP were Teff, Sorghum, Maize, and other cereals from July through November. Due to the low rainfall amount and high rate of evaporation and transpiration during the Belg rainy, there was no crop grown during this period i.e. farmers were producing once a year. But now, with the use of ground water since 2005, farmers are producing twice a year. In addition to the above cereals, cultivation of the most commercial crops in the country such as tomato, onion and pepper is possible during the dry season i.e. from March/April to June/July. According to this research, as the KGVDP proposed, since 2009 farmers were producing three times a year. Also it mentioned comparisons of the crop water requirement for the three commercial vegetables and the actual ground water delivered to the crops show that the amount of water extracted is more than the crop water requirement.

On an average, ground water table declines by 53 cm for current pumping rate, 0.28 cm for onion CWR, 0.31 cm for tomato CWR and 0.31 cm for pepper CWR per year. This implies that the more the ground water is pumped out, the higher the rate of decline, unlike recharge to the ground water. The researcher mentioned that measurement of the water table depth in December 2008 on Hormat-Golina No.4 well indicated that the area irrigated was only 75% of the total area irrigable by the well. It was decreased by about 50cm from the previous year. Water table depth at the well testing time was 17.5 m, and after one year it was declined to 17.05 m. Finally, the researcher has concluded that the maximum water table reduction rate is about 2 m per year for the coming 10 years.

Getaneh Kinfu, (2010), states that the valley floor consists of unconsolidated basaltic alluvial deposit which originates from the western and eastern escarpments. The thickness of the sediment ranges from 30-150m, the average aquifer thickness reaches 90m. Generally, the maximum aquifer thickness of this unit lies across the center of the valley and its minimum lies close to the western escarpment and around volcanic hills within the valley. Golina, Hormat and Kelkelit streams are the main streams that drain the Kobo valley. Golina stream is perennial whereas the other streams are intermittent. Golina has a very limited base flow and Hormat has significantly low seepage flow through the streambed sediment. The main stream (Golina) that drains the western highlands gets its base flow from the volcanic aquifer and losses some amount when it reaches the valley floor (the alluvial deposits). Near the out let to Afar, the Golina stream gains some amount as its flow increases down stream. On the other hand, the Hormat stream collects some seepage flows from the western highlands and loses into the alluvial sediments along the stream course. The colluvial sediments on the sides and feet of the highlands, especially on the west, are very coarse grained and highly permeable. Recharge in this area is generally assumed to very minimum from direct precipitation. However, the valley floor gets recharge from runoff along escarpments and stream leakage which flow down the highlands. The runoff from the highland area flow out to the valley floor along two mainstream channels, Golina and Hormate streams, and few along Keleklit stream.

The study assumes that the recharge from excessive irrigation was assumed to be negligible, because the current irrigation system uses drip and sprinkler method.

CO-SAERAR (1997), stated that the regionalization approach was used to estimate the annual surface runoff of the Golina River, which was ungauged , using the data from the gauged Borkena river. The criteria used to consider this method are: Geographical location, climate factors and Runoff generating factors (slope, catchment's characteristics, and precipitation) of the gauged and the ungauged catchments. The method has been found to be satisfactory with an error of less than 10% when checked against the measured data of the Borkena River which is located in similar environment south of the Kobo valley. The Borkena River was considered as ungaged river for testing the regionalization approach.

According to Kinzelbach W. et. al .(2002), the rate of recharge is the single most important factor in the analysis and management of groundwater resource in arid and semi-arid regions. The methods that are used to estimate groundwater recharge are: Direct measurement, Water balance method, Darcyan method and Tracer method
Every method has its strengths and weaknesses, but combination of methods becomes much stronger.

Xu Y. et.al, (2003), Groundwater recharge is an addition of water to groundwater reservoir. There are four main modes of groundwater recharge. These are: Downward flows of water through the unsaturated zones reaching the water table, Lateral and /or vertical inter aquifer flow, Induced recharge from nearby surface water bodies resulting from groundwater abstraction and Artificial recharge such as from borehole injections or man-made infiltration ponds.

The main sources of recharge are: rainfall, surface water bodies (ephemeral or seasonal rivers, lakes) and irrigation losses.

According to this document, the promising methods those are used to estimates groundwater recharges in arid and semi-arid areas are: Chloride mass balance method (CMB), Cumulative rainfall departure (CRD), Groundwater modeling and saturated volume fluctuation (SVF).These methods have in common that they estimate recharge based on linking specific information from the atmosphere, unsaturated and saturated zones. The limitations and data requirements of CMB and CRD were presented in this document.

CMB should not be applied in areas underlain by evaporates or areas where upconing or mixing of saline (ground) water occurs. Required data are: long term averages of precipitation, chloride content of precipitation, chloride content of groundwater and dry chloride deposition.

CRD cannot be applied in areas where there are no groundwater level fluctuations. This method should only be applied to unconfined aquifers. The required data are: monthly rainfall records, water levels, borehole abstraction, aquifer properties including storativity and size of recharge area.

Groundwater indicators working group, (2007), stated that though groundwater is the main and safest source used for water supply and agricultural and particularly irrigation in many parts of the world, the managerial control over groundwater resource development and protection is often poor and this has lead to uncontrolled aquifer exploitation and contamination. Intensive abstraction from aquifer may affect springs, streams, base flow, groundwater piezometric levels, groundwater storage, and wetlands and can produce land subsidence. As tools, the group have developed and proposed ten groundwater sustainability indicators. These are: Renewable groundwater resources per capita, total groundwater abstraction divided by groundwater recharge, total groundwater abstraction divided by exploitable groundwater resources, groundwater as a percentage of total use of drinking groundwater, groundwater depletion, total exploitable non-renewable groundwater resources divided by annual abstraction of non renewable groundwater resource, groundwater vulnerability, groundwater quality, groundwater treatment requirement and dependence of agricultural population on groundwater.

Each indicator describes a specific aspect of groundwater system and /or process and is based on aggregation of selected variables, both quantitative and qualitative. The indicators can be expressed as an index.

Definitions' of important terms:

Total groundwater abstraction means the total withdrawal of water from a given aquifer or groundwater unit by means of wells, boreholes, springs and other ways for the purpose of public water supply and agricultural, industrial and other usage.

Exploitable groundwater resources means the amount of water that can be abstracted annually from a given aquifer under prevailing economic, technological and institutional constrains and environmental conditions.

Non - renewable groundwater – is groundwater resource available for extraction of necessity over a finite period, from the reserves of an aquifer which has a very law rate of average annual renewal but a large storage capacity.

Some of the sustainability indicators are explained as:

1. Renewable groundwater resources per capita,

This indicator is defined as the total amount of renewable groundwater resource, without considering groundwater quality but excluding brackish and saline water.

The indicator expresses the total amount of renewable groundwater (m^3 per year) per capita. The objective of this indicator is to estimate the amount of good (safe) drinking water , water for irrigation (particularly) for irrigation , for industry and for ecosystem that exists, in a defined area. This amount of available groundwater in relation to the number of people using it becomes an important factor to the social and economic development of the people.

2. Total groundwater abstraction x100/ groundwater recharge

   This indicator is expressed in percentage and it shows the sustainability of the groundwater development. Three scenarios are proposed for interpreting the indicator values and to give significance to the estimated value

   Scenario 1: abstraction ≤ recharge i.e. < 90% implies the groundwater development is sustainable.

   Scenario 2: abstraction = recharge i.e. = 100% but doesn't directly translate to sustainability groundwater development because there could be aquifers at local level that are over abstracted. Hence, it is advisable to consider further factors the application of this indicator.

Scenario 3: abstraction > recharge i.e. > 100% implies the groundwater development is not sustainable.

3. Total groundwater abstraction x100/exploitable groundwater resources

The indicator expresses the degree of development of groundwater. Here are also three scenarios.

Scenario 1: abstraction ≤ exploitable amount of groundwater i.e. describes under developed groundwater resources probably with potential for further development.

Scenario 2: abstraction = exploitable amount of groundwater i.e. implies developed groundwater resource.

Scenario 3: abstraction > exploitable groundwater resource i.e. describes over exploited groundwater resource.

4. Groundwater as a percentage of total use for drinking water

This indicator expresses the relation (in percentage) between groundwater and surface water, which are used for drinking supplies. Hence, it indicts groundwater dependency.

5. Groundwater depletion

It is defined here, based on the following relation:

∑ Areas with a groundwater depletion problemx100/ total study area

As any groundwater exploitation leads to water level decline and affects groundwater storage. Hence, the reliable indicators for groundwater dplition are: change of base flow, change of groundwater quality characteristics, land subsidence and strong groundwater level decline associated with loss of springs or production well yields.i

6. Total exploitable non-renewable groundwater resources x100/ annual abstraction of non renewable groundwater resource

7. Groundwater vulnerability

Vulnerability of groundwater is a relative, non measurable dimensionless property. The concept of groundwater vulnerability is based on the assumption that the physical environment may provide some degree of protection to groundwater. It is a natural property of a groundwater system that depends on the sensitivity of that system to natural and human impacts. The term natural (intrinsic) vulnerability is defined solely as a function of hydrogeological factors, the characteristics of an aquifer and overlying soil and unsaturated geological material. Specific vulnerability of groundwater system, mostly assessed in terms of the risk of the system becoming exposed to contamination loading, is not considered in the proposed groundwater vulnerability indicator.

The following variables are generally used to assess natural groundwater vulnerability: net recharge, soil properties, unsaturated zone lithology and thickness, groundwater level below ground, aquifer media and aquifer hydraulic conductivity. Parameter weightings and rating meters are usually implemented to express relationships between the variables and to reflect their importance for groundwater vulnerability assessment.

1.9 Approaches and methodology

1.9.1 Pre-field work

Collection of secondary data such as meteorological data, geological map, topographical map 1:50,000, hydrogeological map, geophysical data, pump test data, DEM (30m resolution) and on Population size, livestock distribution, common crop, current water supply of the study area was made. Moreover, published, unpublished research works, Geological and hydrological, Hydrogeological report and information on socio- economy of the areas were collected.

1.9.2 Field work

During the field work, Secondary data collection such as meteorological data for conformation, geophysical, pump test data from regional bureau and local private organizations, on Population size, livestock distribution, common crop, current water supply of the study area –for conformation, current water use of the areas, future irrigation plan or investment plan of the regional state, additional Hydrogeological reports of the areas and other relevant information from concerned organizations was made. In addition to these, primary data collection water sample collection from wells and springs –for chemical analysis, discharge data from springs and wells and if possible from streams, and information on total irrigated /irrigable land , common crop types and potential livestock of the areas and current water use and management practices of the study areas.

1.9.3 Post field work

After the field work secondary data compilation, analysis and interpretation to estimate PET, average P, crop water consumption and surface runoff was made. Moreover, estimating current water consumption and forecasting future water demand was made. To delineate the study area satellite image (30m resolution) analysised using ARC VIEW 3.2. Recharge estimation using water balance method and chloride mass balance method. Cumulative rainfall departure (CRD) which is based on water level fluctuation is used to evaluate and estimate the water table fluctuations. The groundwater quality vulnerability is evaluated by studying the characteristics of the unsaturated and saturated zones, the depth of the groundwater table, presence or absence of soil and its thickness. At the end, the sustainability of the groundwater is evaluated using sustainability indicators.

CHAPTER TWO

GENERAL OVERVIEW OF THE STUDY AREA

2.1 Locations and area extent

The Raya valley is located in northern part of Ethiopia about 600Km from the capital Addis Ababa and southern part of Tigray regional state at 170 Km from the capital Mekele. Geographically, it is bounded within 12 ^{0} 5$^{'}$-12 ^{0}58$^{'}$ north latitude and 39 ^{0}20$^{'}$ -39 ^{0} 53$^{'}$east longitude. The total area of the basin comprising the Raya valley is approximately 2579 Km^2 . The Raya valley is bounded by the Maichew Mountains in the north and the central Ethiopia high lands on the west and Chercher Mountains from east and Waja village in the south (Fig.2.1).

The valley is found in the northern part of Ethiopia, about 570 Km from the Capital Addis Ababa and about 20km south of the Raya valley. It is bounded within 11^{0} 55$^{'}$ 40$^{''}$ – 12^{0} 10$^{'}$ 11$^{''}$ north latitude and 39^{0} 22$^{'}$ 30$^{''}$ – 39^{0} 46$^{'}$ 44$^{''}$ east longitude covering a total area of 1351Km^2 including the Waja-Golesha area. The area 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 (Fig.2.1).

Both study areas are part of inter connected Valley of the Ethiopian Rift system. Hydrologically, they are found in the western Denakil river basin. They have good network of roads and they are easily accessible.

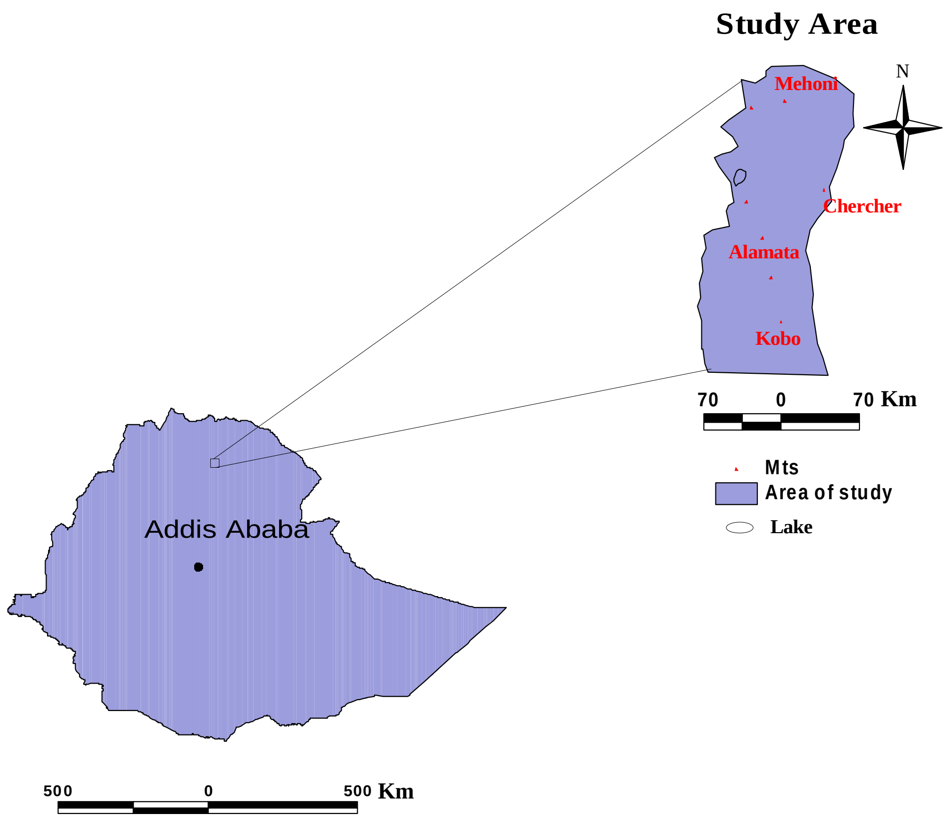


Fig.2.1 Location of the study area

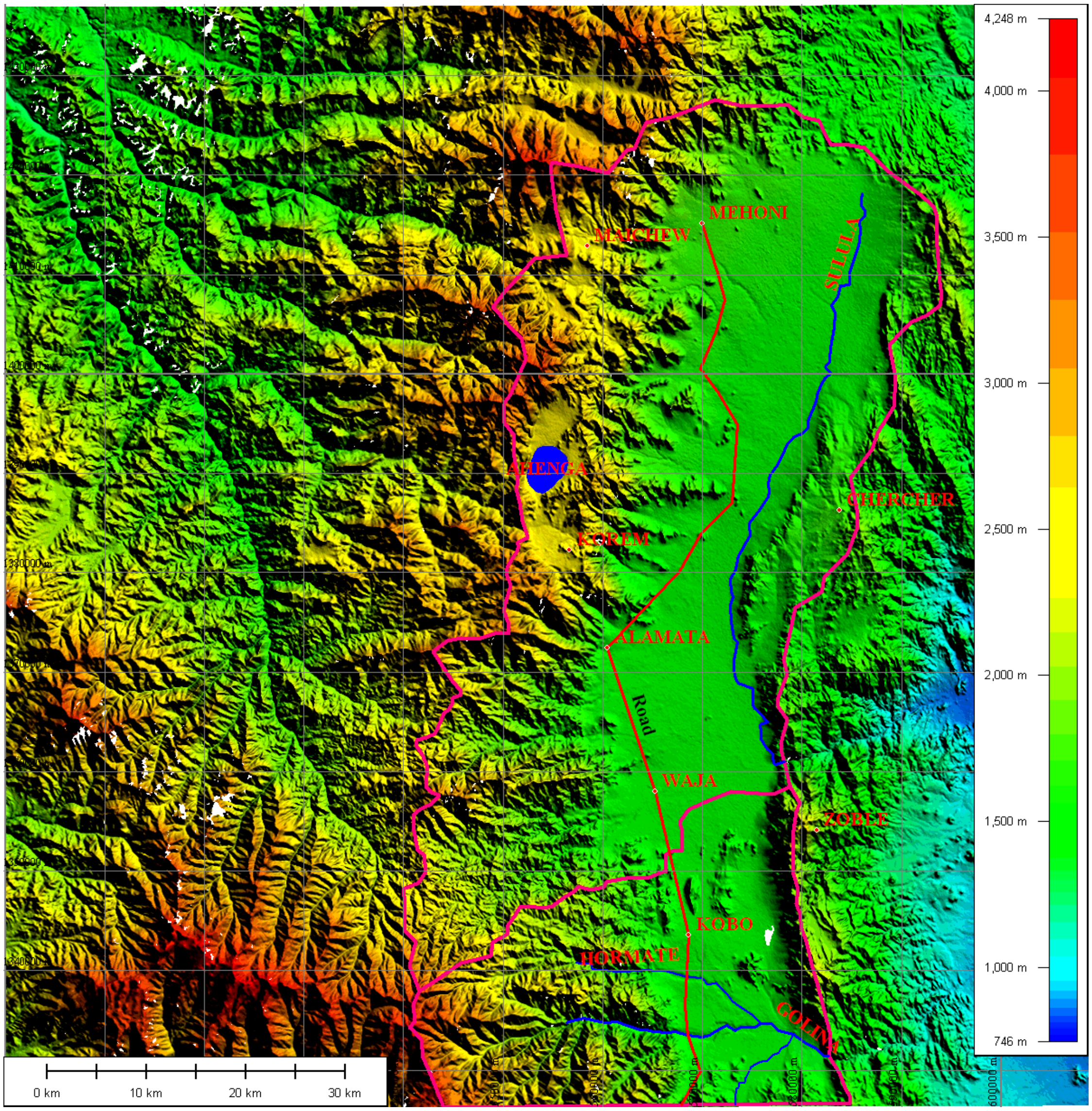


Fig 2.2 DEM of the study area

2.2 Climate

The position of inter –tropical convergence zone (ITCZ), seasonal variations in pressure systems and air circulation, results in the seasonal distribution of rainfall over the study areas. This low pressure area of convergence between tropical easterlies and equatorial easterlies causes equatorial disturbance (Daniel Gemechu, 1977). The areas have a semi-arid climate. The distribution of rainfall over the highland areas is influenced by orographic effects the areas are characterized by a bimodal rainfall pattern with a short rainy season " Beleg" from March to April and a long rainy season" Keremt" from July to September with a peak in August(see section 3.2.1.) . The other months of the year are generally dry. The pattern of mean monthly temperature and other patched climatical variables which were collected from metrological stations located around the study area are described below.

The climatic variables such as maximum and minimum temperature, wind speed, relative humidity sun shine duration are important for the estimation of evapotranspiration. For the analysis of evapotranspiration, these variables are computed from eight metrolodical stations. The considered stations are: Kobo, Waja, Alamata, Korem,Maichew,Mehoni and Chercher. All stations are found within the study area, except the Chercher station. The metrological data of these stations is not complete due to the occurrence of missing data. For example the Alamata station has thirteen unrecorded years of temperature. Where as the Maichew has six unrecorded years of the same climatic variable. This limitation may affect the analysis of surface and subsurface water of a catchment which takes in to consideration a long time metrological data record.

To overcome this limitation, 41 years (i.e. 1953-2004) patched metrological data of the (MOWR, 2008) is used. The station's climatical variables considered for hydrological study of the Raya valley and Kobo valley are presented below.

Table 2.1 Location and Elevation of the metrological stations

Name of station	X ,M UTM	Y ,M UTM	Z .M Elevation
Alamata	560502	1372456	1547
Chercher	583783	1386254	1786
Mehoni	570019	1415122	1767
Korem	556673	1382295	2466
Maichew	558432	1412871	2438
Waja	565315	1357995	1446
Kobo	568641	1343604	1524
Korem	556673	1382295	2466

2.2.1 Temperature

This study uses value of the mean monthly temperature of the Kobo, Waja, Alamata, Korem, Maichew, Waja and Mehoni stations for the estimation of hydrological parameter of the study area (Table 2.2). The mean annual temperature of the study area is 23.33C˚.

Table 2.2 Mean monthly temperature (c˚) used (1953 to 2004)

T	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
AMIN	11	13	14	15	16	17	17	16	15	14	13	12
AMAX	27	28	29	30	31	33	32	30	30	30	28	27
MMT	19	21	22	23	24	26	25	23	23	22	21	20

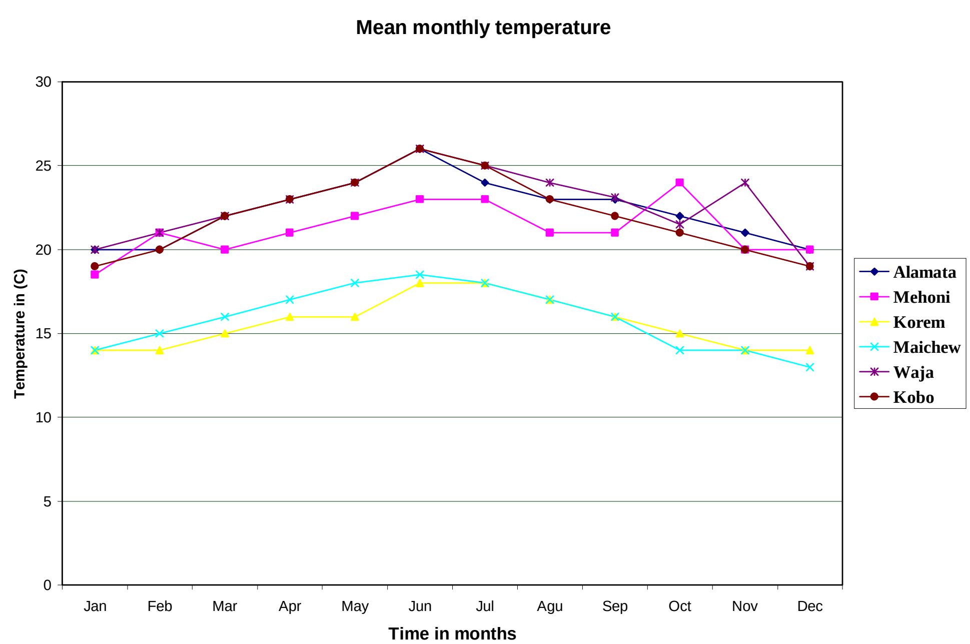


Fig.2.3 Mean monthly temperature variation of study area (1953 to 2004)

2.2.2 Wind speed, Relative humidity, and sun shine duration

The climatic variables such as sun shine duration; wind speed and relative humidity of the eight stations are presented in the table 2.3 below.

Table 2.3 Climatic variables together with recording Stations name (1976 to 2005)

	SSD (mean)		**RH (mean)**			**WS (mean)**	
Months	Kobo	Maichew	Kobo	Maichew	Mehoni	Kobo	Maichew
Jan	7.86	6.93	59.52	61.15	53.5	1.89	1.12
Feb	7.68	8.01	56.54	61.8	54.7	2.06	1.23
Mar	8.05	7.41	51.48	62.59	53.48	2.11	1.34
Apr	8.14	8.49	52.39	56.35	52.83	1.9	1.32
May	8.38	8.89	42.46	51.1	52.98	1.68	1.41
Jun	6.62	7.2	32.93	39.89	58.74	1.94	2.27
Jul	5.68	4.95	46.2	60.93	67.28	1.92	3.34
Aug	6.19	5.13	57.04	64.2	63.83	1.6	2.48
Sep	6.67	7.06	61.11	61.7	60.96	1.2	1.29
Oct	8.58	7.64	53.26	62.13	54.5	1.3	1.18
Nov	9.13	8.08	45.5	59.8	55.07	1.46	1.11
Dec	8.28	7.78	53.67	62.61	53.52	1.61	1.12

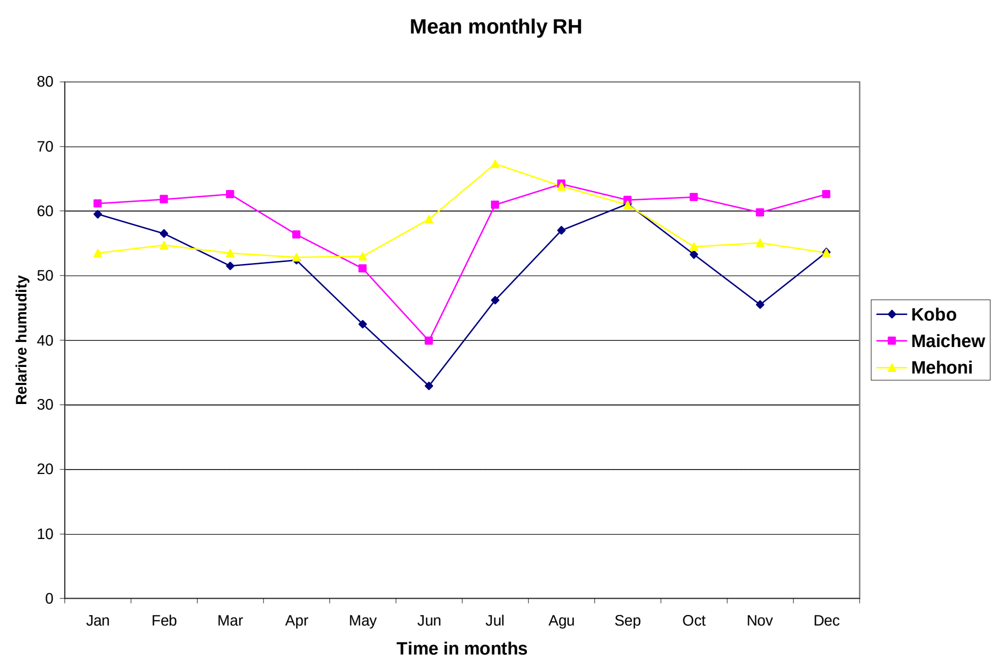


Fig 2. 4 Monthly mean relative humidity of the study area (1976 to 2005)

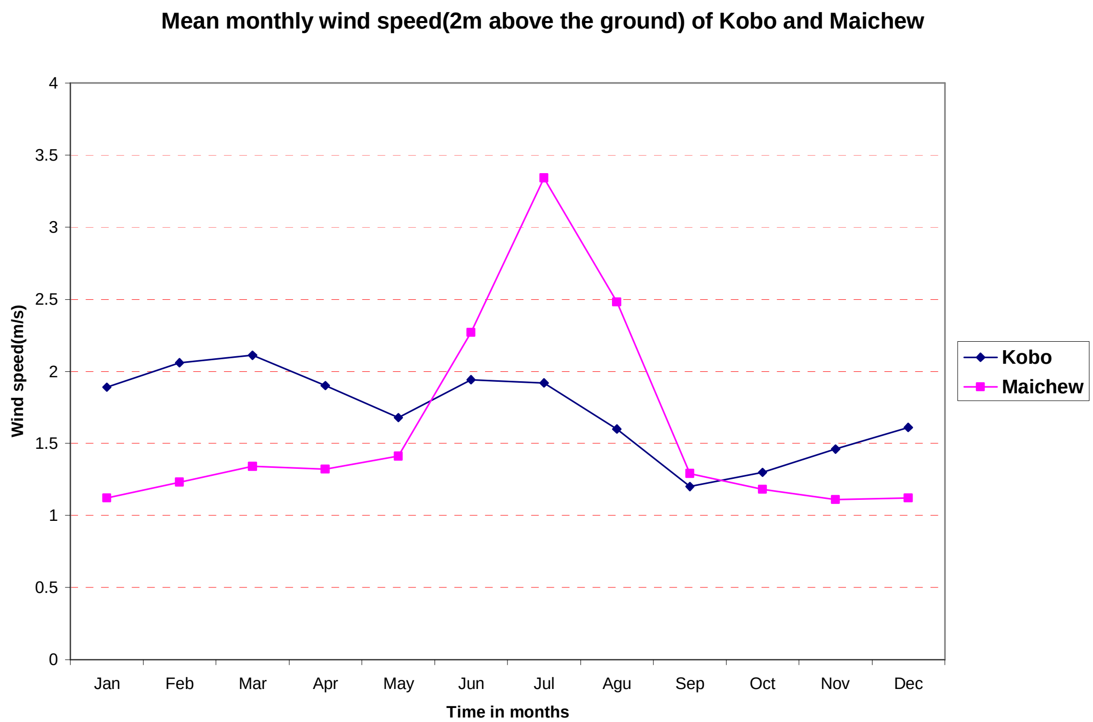


Fig.2.5 Mean monthly wind speed of study area (1976 to 2005)

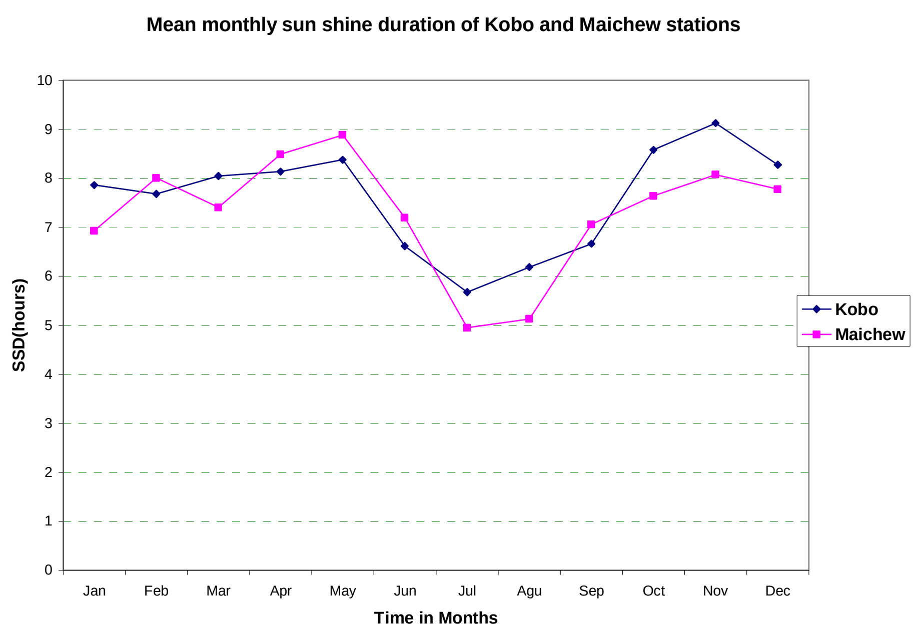


Fig.2.6 Mean monthly Sunshine duration of study area (1976 to 2005)

2.3 Land use and land cover

Identification of the land use and land cover is important to study the recharge amount of the study area. The land use and land cover of the concerned area (Raya Valley and Kobo Valley) are described below. Hence, around 89% of the Raya Valley is covered by Vegetation and the Vegetation cover of the Kobo Valley is around 96%.

2.3.1 Raya Valley

The area consists of five land use and land cover types. These are: forest, agricultural area, water, woodland and bare land. The percentage coverage of the land covers are presented in the table 2.4. As it is shown from the table the woodland and agricultural areas are the dominant land cover class in the area (Table 2.4 and Fig.2.5.)

2.3.2 Kobo Valley

This study area comprises the Waja-Golesha sub basin and Hormate-Golina sub basin. The former is extremely dominated by Agriculture land and wood land. The latter sub basin consists of four types of land cover unites (Getaneh Kinfu, 2010). These are forest, agricultural area, woodland and bare land. Agricultural and wood lands are the dominant land use units (Fig 2.6).

Table 2.4 Land use and land cover types and percentage coverage of Raya area.

S.N	Land cover	Coverage in %
1	Wood land	49.7
2	Bare land	10.4
3	Agricultural area	37.9
4	Forest	1.4
5	Water	0.6
	Total	100

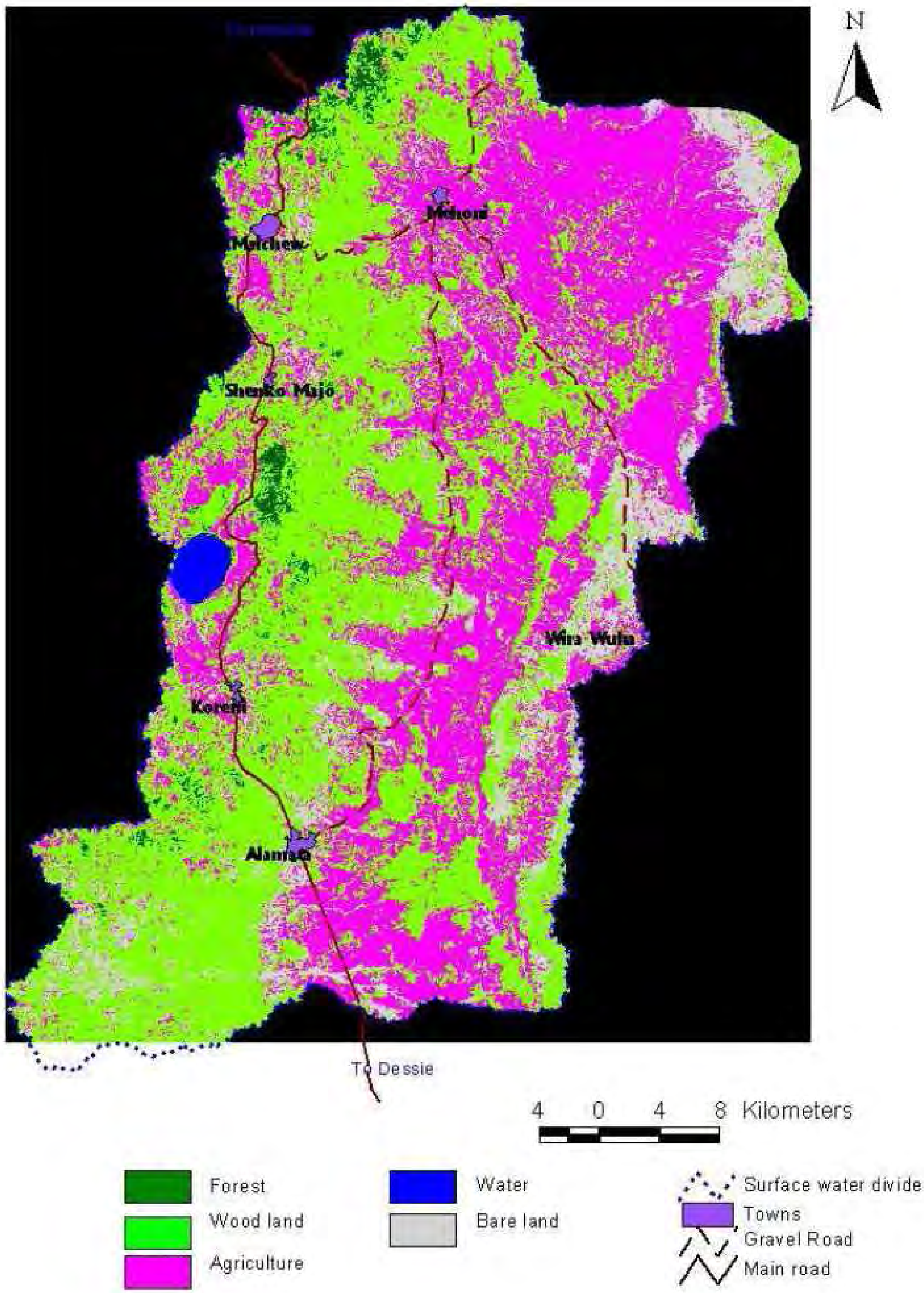


Fig.2.7 Land use and Land cover of the Raya valley (Dessie Nedaw, 2003)

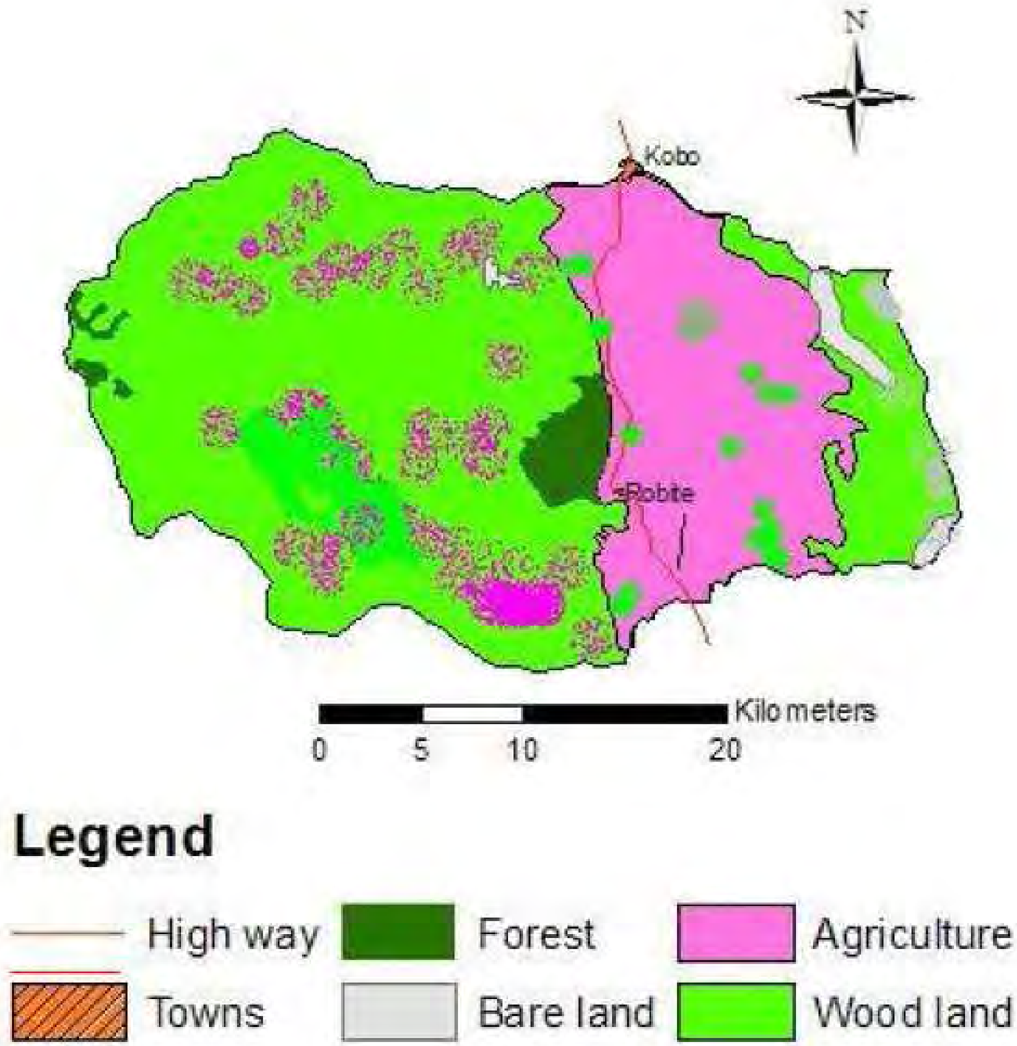


Fig 2.8 Land use Land cover of the Hormate- Golina sub - basin (Getaneh Kinfu, 2010)

2.4 Drainage

The Raya valley comprises of several drainage units which mainly emerge from the western highlands and partly from the eastern highlands. The streams, which are intermittent, originate at the western highlands and some of them make their final destination, with parallel flow west-east direction, at the floor of the valley. Where as others join the major river system of the Sulula river, which have N-S flowing direction, located to the eastern periphery of the valley. The Sulula River cuts the valley the eastern side of the hill at Selembir, and flows into the Afar depression.

The Kobo valley consists of three main streams namely Golina, Hormat, and Kelkelit that originate from the western highlands and drain to the floor of the plain. The Golina is the perennial stream whereas the other to streams is intermittent. The Golina stream collects the runoff to the valley portion and discharge it to the Afar depression at the south-eastern part of the valley.

2.5 Population size and Growth rate

The population size of the Endamehoni, Raya Azebo, Alamata, Ofela and Kobo Weredas, which are found in the study area, is presented in the Table below. The description was collected from the report of the second (1994) and third (2007) population and housing census of Tigray and Amhara regions which was published by the CSA. The population size doesn't consider the migration characteristics of the Weredas. The first population and housing census which was conducted in 1984 was not considered, as it included only the urban part (population and housing census, 1994).

Table 2 .5 Population size of the study areas

Name of Weredas	1994			2007		
	Urban	Rural	Total	Urban	Rural	Total
Endamehoni	20,368	61,289	81,657	2,985	81,741	84,726
Raya-Azebo-Wereda	8,047	79,591	87,638	16,055	119,984	136,039
Ofela- Wereda	17,152	107,332	124,484	15,850	126,953	142,803
Alamata-Wereda	32,229	61,430	93,659	4,563	80,796	85,359
Kobo- Wereda	28,706	146,852	175,558	33,135	188,759	221,894

2.6 Agronomy and irrigation

The Raya and Kobo valleys are the most productive farming areas in the Tigeray and Amehara regions in terms of crops and livestock. The agro ecological zones of the Raya valley are Raya azebo and Alamata woredas. The agro ecological zones of the Kobo valley are the Kobo woreda and Waja-Harosha areas. These woredas are characterized by flat plains and lower foot slope landforms. The area receives bi-modal rainfall with erratic distribution and therefore the bi-modal pattern of the rainfall is not consistent. The mean annual rainfall of the Raya valley varies from 540-850mm and that of Kobo valley ranges varies from 400-760mm. The main rainy season (Meher) lasts from end June to early September and the highest amount of rain is recorded in July & August where as the short rainy season (Belg) starts in February and ends in end March. Soils are mostly loam and silty loam to clay loam texture with better water holding capacity. The soils are deep and moderately deep and are suitable for irrigation.

Table2.6 Existing Meher Cropping Pattern & operational calendar (Alamata Woreda)

No	Crop type	Area	Yield qt/ha	Total Production (qts)	Operation calendar			
		Ha			Ploughing	Sowing	Weeding /hoeing/	Harvesting
1	Sorghum	10,699	22	235378	Jan -Mar	Apr-may	June-Aug	Nov. -Dec
2	Teff	15,262	11	167882	Feb-may	June-july	July-aug	Oct-nov
3	Barley	2,088	16	33408	Apr-may	June	July-aug	Oct
4	Wheat	1,710	15	25650	Apr-may	June	July-aug	Oct
5	Maize	1,465	19	27835	Jan -Mar	Apr-may	June-Aug	Nov. -Dec
6	Broad bean	826	11	9086	Apr-may	June	July-aug	Oct-nov
7	Field pea	889	10	8890	‘’	‘’	‘’	Oct
8	*Abysinicum pea*	69	8	552	‘’	‘’	‘’	‘’
9	Sesame	125	6	750	Feb-may	June	July	Oct
10	Lentil	105	4	420	-	June	-	Sept-oct
11	F.millet	500	16	8000	Feb-may	June	July-aug	Nov-dec
12	Millet	306	19	5814				
13	Nigger seed	25	5	125	-	June	July-aug	Oct
14	Line seed	35	5	175	-	‘’	‘’	Nov-dec
15	Chick pea	180	6	1080	July-aug	End Aug	-	Dec
	Total	34,284	173	525,045	-	-	-	-

Source: - Woreda rural development & Agricultural office as cited from MOWR ,2008

Table 2.7 Existing Meher Cropping Pattern & operational calendar (Raya Azebo Woreda)

No	Crop type	Area	Yield	Total	Operation calendar			
		Ha	qt/ha	Production (qts)	Ploughing	Sowing	Weeding /hoeing	Harvesting
1	Sorghum	16,353	34	556,002	Jan -Mar	Apr-may	June-Aug	Nov. -Dec
2	Maize	211	32	6752	‘’	‘’	‘’	‘’
3	Sesame	126	4.6	580	Feb-may	June	July	Oct
4	Wheat	800	17	13,600	Apr-may	June	July-aug	Oct
5	Ground nut	1.25	10	13	‘’	‘’	‘’	End sept
6	Chick pea	1539	12	18,468	July-Aug	End Aug	-	Dec
7	Grass pea	162	11	1782	‘’	‘’	-	‘’
8	Total	19,192	-	597,197	-	-	-	-

Source: - Woreda rural development & Agricultural office as cited from MOWR ,2008

Table 2.8 Existing Irrigated Cropping Pattern & operational calendar (Alamata Woreda)

No	Crop type	Area	Yield qt/ha	Total	Operation calendar		
		Ha		Production (qts)	Ploughing	Sowing	Harvesting
1	Onion	673	90	60570	Dec-Jan	Feb-mar	End may-june
2	Tomato	76.25	120	9150	‘’	‘’	‘’
3	Cabbage	11.9	80	952	‘’	‘’	‘’
4	Pepper	186.9	7	1308	‘’	‘’	‘’
5	Total	948.05	-	71,980	-	-	-

Sources: - Alamata Woreda Rural Development & Agriculture Office as cited from MWOR,2008

Table 2.9 Existing Irrigated Cropping Pattern & operational calendar (Raya Azebo Woreda)

No	Crop type	Area	Yield qt/ha	Total	Operation calendar		
		ha		Production (qts)	Ploughing	Sowing	Harvesting
1	Onion	87.5	90	7875	Dec-Jan	Feb-mar	End may-june
2	Tomato	60.5	120	7260	‘’	‘’	‘’
3	Cabbage	100	80	8000	‘’	‘’	‘’
4	Pepper	60.25	7	421.75	‘’	‘’	‘’
5	Potato	26	100	2600	‘’	‘’	‘’
7	Coffee	70	5	350	Jan-mar	June- july	‘’
8	Orange	7	50	350	‘’	‘’	‘’
9	Chat	135	20	2700	‘’	‘’	‘’
	Total	572.25	-	30,466.8	-	-	-

Sources: - Raya- Azebo Woreda Rural Development & Agriculture Office as cited from MWOR,2008

CHAPTER THREE

GEOLOGY AND HYDROLOGY

3.1 Geology

3.1.1 Lithology

The geology of the study area is covered with a trap series of the Ashenga basalt, which is dominantly composed of alkaline olivine basalts and tuff, rare rhyolites from fissures and dissected by dikes and sills (WWDSE, 2006). The Ashange basalt is strongly weathered basalt without clear stratification having a thickness of several hundred of meters. The basalt rock is mainly found on the plateau as well as on the western and eastern escarpment of the areas.

The reworked sedimentary materials from the plateau and escarpments covered the valley floor. The thickness of this sediments varies from few meters in the west and east part of the valley to more than hundreds of meters in the central part. The sediments are unsorted coarse gravels and cobbles on the west and get finer to the center. Data from borehole lithological and geophysical surveys in the study areas indicates that the central part of the study areas comprise of the intercalation of gravels, gravelly sand, sand silty sand, silty, silty caly and clay. Generally, according to (Dessie Nedaw, 2003), the lower unit of the basin fill is believed to be a lake deposit while the upper one is a river deposit.

3.1.2 Geological Structure

The structure of the study area is characterized by asymmetric faults developed a graben which is called Corbetta.The fractures have similarities with the structures that developed the rift. It is found on the western outskirts of the afar depression. The characteristic pattern of the structures is step fault scheme. The elevation of the study area decreases as one goes from west to east and this is governed by the E-W trending faults resulting in a south ward tilting and N-S faults responsible for the easterly tilting. The fracture pattern does not signify a single direction.

In general the dominant strike direction is NNW – SSE and NNE – SSW. Some of the minor lineaments shows a kind of east- west strikes which in some cases are followed by the rivers flowing down through the plateau and the escarpments (Dessie Nedaw, 2003).the E-W and ENE-WSW running cross faults with minor displacement are also seen. The latter faults seem to have given outlet to Sulula and Golina rivers toward Afar after damming (Sileshi Mamo, 2007).

3.2 Hydrology

Water is found in the earth's atmosphere as vapor, on the earth's surface (surface water) and within its subsurface (groundwater). It circulates among these three divisions. The science that deals with the continuous circulation of water, which is called hydrologic cycle, is hydrology. Hence, hydrology plays critical functions in groundwater recharge. The basic components of the hydrologic cycle such as, precipitation, runoff, evapotranspiration, recharge and groundwater discharge are dealt in the study areas. Recharge, which is one of the most important parameter in groundwater management, is presented in section 3.4.1.

3.2.1 Precipitation.

The depth of precipitation that a storm releases over an area may vary from a maximum value at one or more points to zero at the storm's boundary. This variation poses problems in determining the average precipitation that falls on a basin affected by the storm. The average depth is commonly calculated in one of three ways: Arithmetic mean, Thiessen, or Isohyetal methods. The simple method to calculate precipitation is the arithmetic mean of precipitation measured at a number of stations. This procedure ascribes equal weights to all measurements, and is used when rain-gauges are uniformly distributed and the topography is flat. The Thiessen method weights the precipitation measured at each station by the area that the station represents. It is appropriate when orographic effects are negligible and rain-gauges are not spaced uniformly. The Isohyetal method uses the observed precipitation data as the basis for drawing contours of equal precipitation (isohyets), and then weights the average precipitation of adjacent isohyets by the area between the isohyets.

The method is suitable for large areas, especially those in which orographic effects may be present (Tenalem and Tameru 1998). The method of estimating rainfall depth for a specified area using Isohyetal contours is a more accurate method than the Thiessen Polygons (as cited in Tatiana et.al 2010). Therefore, the isohyetal contours were used to represent the spatial distribution of rainfall.

3.2.1.1 Data collection

The precipitation records of eight stations were collected. Locations are shown in Fig. since these stations have missing data of several months and years; Corrected records (1953-2004 years) of the seven stations are available from the minister of water resource. But uncorrected different years records of these stations are available form the national metrological agency (NMA) (see Appendix 5). Even though Zoble is out of the study area, its rainfall records are included in the analysis. When these records are adopted, relevant information about the type of rain-gage, the height above ground where the gauge was placed and whether the gauges meet the criteria of being free from vertical obstacles (e.g. trees or buildings) was not available.

Table 3.1 Mean monthly and annual rainfall of stations (1953-2004, except Zoble)

Stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	MAR
Alamata	38.6	28.07	85.5	101	50.57	10.84	125.4	211.21	51.7	22.8	20	30	769
Chercher	27.1	55.24	30.7	37	53.92	52.58	121.1	173.72	60.36	46.7	17.8	6.34	683
Mehoni	16.9	23.56	82.5	84.4	37.78	36.92	59.16	111.38	65.62	14.36	28.62	9.06	590
Korem	61.9	50.24	86.9	82.6	91.52	24.6	169.94	224.12	74.32	64.34	33.32	30.22	1000
Maichew	30.7	25.88	54.8	80.2	67.6	28.68	148.44	194.8	68.98	48.3	23.02	14.56	786
Waja	29.7	41.78	52.8	78.3	60.26	29.5	100.6	183.72	59.78	29.06	20.74	16	702
Kobo	18.7	22.68	40.8	62.2	52.68	13.94	129.94	176.92	63.2	49.76	16.7	13.24	655
Zoble	43.4	18.6	72.7	88.7	56.76	12.82	146.33	226.43	88.79	58.47	29.38	16.9	828

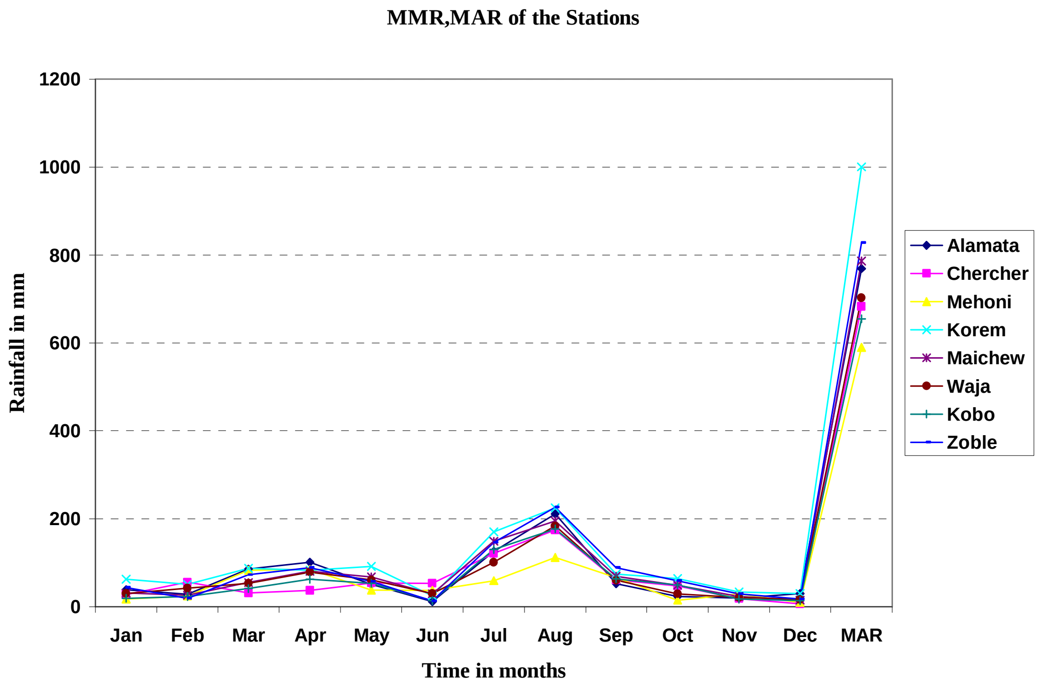


Fig. 3.1 Mean monthly and annual rainfall of the study area (1953 to 2004)

3.2.1.2 Estimation of Precipitation

Mean monthly and annual totals of the eight stations are computed using Microsoft Excel. Where as the mean precipitation of the catchments (i.e. Raya valley and Kobo –Golina) are estimated using isohyetal method.

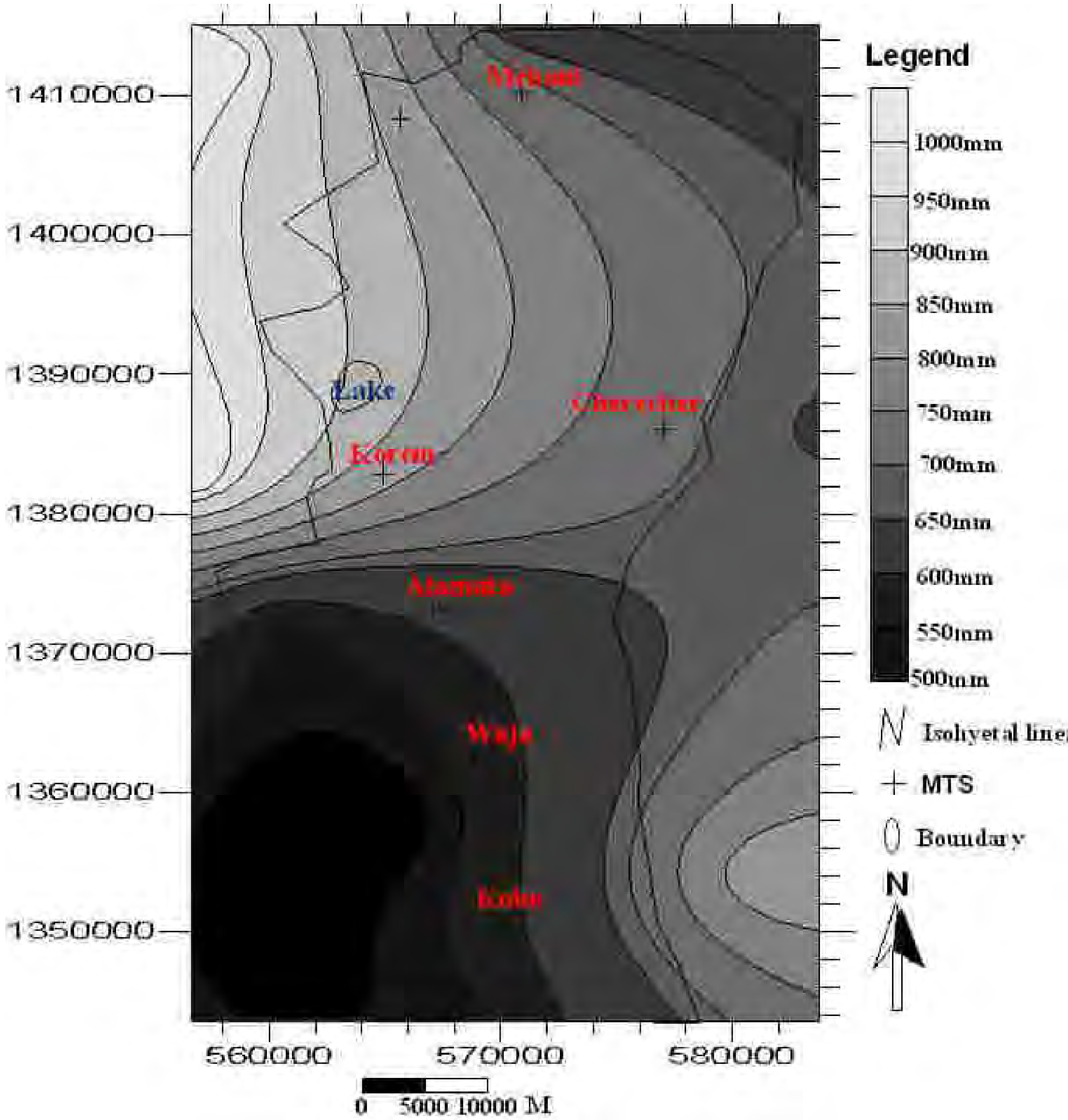


Fig.3.2 Rectified Isohyetal map of the study area

3.2.1.3 Effective Rainfall

The definition of effective rainfall is different, depending on the area, concerned. For example: to canal engineer, the hydrologist refers to that rainfall as effective, which results the rainfall is the runoff from the catchment area. To a geo-hydrologist, that part of rainfall which contributes to the groundwater storage is counted as effective rainfall. For groundwater case, the rise in net height of water table is considered as the effective rainfall (Suresh, 2008).

According to Kobo Girana valley development project (as cited from Abrham Melesse, 2009) effective rainfall is portion of the rainfall amount that can enter in the soil and support crop evapotranspiration. Effective rainfall (P_{eff}) can be computed by different methods considering rainfall of an area under consideration. The project has adopted the method by USDA soil conservation service. Since the average annual rainfall of the Raya valley is greater than 250mm, to estimate the total effective rainfall the following formula are used.

$$P_{eff} = \frac{[P\,(125-0.2P)]}{125} \qquad \text{if } P <= 250mm$$

$$P_{eff} = 125 + 0.1 * P \qquad \text{if } P > 250mm \qquad \text{----------------------(1)}$$

According to the estimation using isohyetal method, the average annual rainfall of the Raya valley and Kobo valley is 813mm, which is greater than 250mm. Hence, the effective rainfall of the Raya and Kobo valleys is 206.3mm.

Table 3.2 Mean annual rainfall using Isohyetal method

		A	B	A*B
Isohyets upper,mm	Isohyets lower,mm	Mean rainfall on area,mm	Area between isohyets,Km2	Weighted mean rainfall
600	550	575	2.28	1311
650	600	625	208.72	130450
700	650	675	159.28	107514
750	700	725	475.72	344897
800	750	775	459.06	355771.5
850	800	825	639	527175
900	850	875	442.7	387362.5
950	900	925	174.3	161227.5
1000	950	975	210	204750
1050	1000	1025	158	161950
			2929.06	2382408.5
Mean annual rainfall				813.36

3.2.2 Surface runoff

The Raya-Kobo valley catchment is characterized by a perennial river, together with numerous seasonal streams which flow into the floor part of the valley. Guguf, Fokisa, Haya + Warabayi,,Beyru, Ula Ula+ Tirk, Dayu ,Hara, ITU, Tengego, Oda, Sulula, Harosh, Hormat,Golina and kelkelit are the rivers which originate from the western high lands and flow to the floor of the valley with the flow direction W-E (Plate 3.1).

The Guguf, Fokisa, Haya + Warabayi,,Beyru are intermittent streams which are found and flow to the Mehoni sub-basin of the catchment area under study. Whereas the Ula Ula+ Tirk,Dayu,Hara,ITU,Tengego,Oda Harosha flow to the Alamata sub-basin. Sulula , which is the longest river in the Raya valley with the outlet at the Eastern escarpment of the study area, flow in the north-south direction collecting stream water from the small intermittent streams of the two sub-basins.The Hormat ,Kelkelit and Golina are located in the Kobo sub-basin with the same flow direction and origin.

Plate 3.1 Hara stream in the E-W direction taken from Gerakasu Mountain

The Golina River, the only perennial river in the Raya-Kobo catchment, has an outlet at the eastern escarpment of the Hormat – Golina cachment. The Hormat and Kelkelit streams join the perennial river at the floor of the catchment.

3.2.2.1 Surface runoff data analysis

All major and small streams of the study area, except the Golina River have no flow data; and this is the major source of error in computing the average value of surface runoff. All the rivers arising from the western escarpment of the basin do not exhibit annual variability, except the Glolina River, with maximum flows occurring in rainy season. One notable feature about rivers draining the Raya-Kobo catchment area is that they gradually lose their flow in the cachment plain due to the porous nature of the area. The flow records of Golina gauging station has been used to estimate the mean monthly records of the other streams of the study area. The estimation uses the regenalization approach. The method has been found to be satisfactory with an error of less than 10% when checked against the measured data of the Borkena River which is located in similar environment south of the Kobo valley. The Borkena River was considered as ungaged river for testing the regionalization approach (Co-SAERAR, 1997).

According to MOWR (2008), as regionalization factor; area, rainfall and runoff coefficient with the following relationship has been used.

$$Q_u = \frac{Q_g * A_u * P_u * C_u}{A_g * P_g * C_g} \quad (2)$$

Where:

Q= monthly runoff of the steams,mm

A= area of the sub-catchment of the streams, Km^2

P= Areal rainfall, mm

C= runoff coefficient of the catchment

U, g= ungauged and gauged respectively.

The most important factor in this approach that should be correctly determined is the runoff coefficient of the gauged and ungauged streams. Though the range of runoff coefficient for the Raya valley is 0.13-0.22, the runoff that leave the mountains area for dam contraction proposed (REST,1998) was calculated taking 0.22 runoff coefficient (as adopted Dessie Nedaw,2003).Where as for that of Hormat- Golina catchment, the mean runoff coefficent is 0.3 (as cited in Getaneh Kinfu, 2010).

Therefore, total runoff of the Raya valley and Hormat-Golina catchment is calculated considering a runoff coefficient 0.22 for Raya valley and 0.3 for the Hormat-Golina catchment. However, true representative total runoff value for the study area remains unsolved. The problem can be solved as long as flow data of the basin is made available. In this regard, the mean value of surface runoff used can best be described as an estimate.

The Raya valley comprises of intermittent streams which originate from the western highlands (Table 3.4). These ungauged streams have discharge only during the dray season which disappear to the floor of the valley with the flow direction of W-E and recharge the groundwater. For the analysis of runoff of the steams, equation 2 with the runoff coefficient of 0.22 and 0.3 for Raya valley and Kobo valley respectively are used.

Golina, Hormat and Kelkelit are the main streams that exist in the Kobo valley. The Golina stream is perennial the other two are intermittent. The streams originate from the western highlands of the valley and have W-E flow direction. The intermittent streams join the Golina River, which has an outlet at the eastern escarpment, at the floor of the valley.

According to MCE (2008), the Golina River has unrecorded discharge though the stream is gauged. In order to generate discharges for the unrecorded data of the Golina,
Hormat and Kelkelit, estimation has been achieved from the discharge records of Mille River, which is found in similar catchments, with regionalization approach (Appendix 6). The basic assumptions during the estimation are: the two systems have similar climatological and hydrological characteristics and they have more or less similar geological setup. The total average annual runoff of the Raya valley, which comprises of 14 intermittent streams, is 268.71MCM, which is equivalent to 222mm. Kobo valleys, which consist of 2 intermittent and one perennial stream, 61.8MCM respectively. The estimation of the total runoff is based on regionalization approach taking the runoff coefficients 0.22 and 0.3 for Raya and Kobo Valleys respectively. The regionalization factor that is used during the estimation of total annual runoff is calculated by multiplying the area of the catchment of each stream by 0.222, which is determined from equation (2).

Table 3.3 Raya valley streams along with area of catchment

Streams	**Area,Km^2**	**Precipitation ,mm**	**Mean annual runoff,MCM**
Golina*	262	813	61.8 equivalent to 235.88mm
Tirke + ulaula	71	813	15.762
Dayu	72.3	813	16.05
Hara	63.6	813	14.12
Ttengago	30	813	6.66
Oda	79	813	17.538
Harosha	154	813	34.188
Mersa	151	813	33.522
Gobu	165	813	36.63
Habro	32	813	7.104
Guguf	124	813	27.528
Fokisa	99	813	21.978
Haya	79.5	813	17.65
Werabeyi	20	813	4.44
Beyra	70	813	15.54
Total annual run off of Raya Valley			268.71,or 222mm

* Gauged stream located in Kobo Valley

3.3 Evapotranspiration

Evaporation (E) is the transfer of water into the atmosphere from a free water surface, a bare soil or interception on a vegetal cover. Transpiration is the process by which the moisture that has circulated through the plant structure is returned to the atmosphere in the form of water vapour. Since it difficult to separate the two processes both are treated as interrelated processes called evapotranspiration (ET). Evaporation is a very complex process and is difficult to quantify, as it is hard to measure the transfer of water vapour directly. Evapotranspiration can be defined as a natural process where water vapour is transferred from both the land surface and vegetation surface evaporation and transpiration processes. There are two types of evapotranspiration: Potential evapotranspiration (PET): the evapotranspiration from a vegetal cover if sufficient water supplied to obtain optimum growth or the maximum amount of vapour which might be transferred under the existing meteorological conditions (water is not the limiting factor).

Actual evapotranspiration (AET): the evapotranspiration from a vegetal cover under the natural or given conditions of supply of moisture or the actual amount of vapour which might be transferred to the atmosphere, depends also on the availability of water to meet the atmospheric demand.

3.3.1 Estimation of evapotranspiration

There are many methods of estimating evapotranspiration. Some of these are: Soil moisture sampling, Lyaimeter experiment, Water balance method and Using Pan. Moreover, evapotranspiration can be estimated using different equations. But this study focuses on: the Thornthwait equation to estimate the PET. The formula relates potential evapotranspiration to temperature and the number of hours of day light between sunrise and sunset and gives figures for the consumptive use of short closed vegetation with adequate water supply.

It has been developed based on observations in limited climatic range. The method uses the following formula:

$$\mathbf{PET=16*[10t/J]^{a}} \qquad \mathbf{(3)}$$

Where:

PET = potential evapotranspiration, mm/month; t=mean monthly temperature (C^o)

$J = \sum j$, j is the temperature value of each month, **$j= (t/5)^{1.514}$** and a is related with **J** using **$a= (675x\ 10^{-9})J^3 – (771X10^{-7})\ J^2 + (179X10^{-4})\ J + 0.492$ or $a= 0.016J + 0.5$.**

Table 3.4 Monthly potential evapotranspiration and average monthly rainfall in mm.

<table>
<tr><td>Months</td><td>T,˚ C</td><td>j</td><td>J</td><td>a</td><td>PET,mm</td><td>AMR,mm</td></tr>
<tr><td>Jan</td><td>19</td><td>7.55</td><td rowspan="12">110.29</td><td rowspan="12">2.43</td><td>60</td><td>33.4</td></tr>
<tr><td>Feb</td><td>21</td><td>8.17</td><td>68</td><td>33.4</td></tr>
<tr><td>Mar</td><td>22</td><td>4.92</td><td>86</td><td>63.3</td></tr>
<tr><td>Apr</td><td>23</td><td>10.08</td><td>95</td><td>76.8</td></tr>
<tr><td>May</td><td>24</td><td>10.75</td><td>106</td><td>58.9</td></tr>
<tr><td>Jun</td><td>25</td><td>12.13</td><td>129</td><td>26.2</td></tr>
<tr><td>Jul</td><td>25</td><td>11.44</td><td>117</td><td>125</td></tr>
<tr><td>Aug</td><td>23</td><td>10.08</td><td>95</td><td>187.8</td></tr>
<tr><td>Sep</td><td>23</td><td>9.42</td><td>86</td><td>66.6</td></tr>
<tr><td>Oct</td><td>22</td><td>9.42</td><td>86</td><td>42</td></tr>
<tr><td>Nov</td><td>21</td><td>8.78</td><td>77</td><td>24</td></tr>
<tr><td>Dec</td><td>20</td><td>7.55</td><td>60</td><td>17.04</td></tr>
<tr><td colspan="5">Mean annual</td><td>1065</td><td>813.36</td></tr>
</table>

T=Temperature (C^o), PET= potential evapotranpiration (mm), AMR= average monthly rainfall (mm)

The mean anuual actual evapotranspiration ($\overline{E}$) of the study area is computed using the formula of Turc, Langbein and Wundit, which is on the basis of data from mean annual precipitation in mm and mean annual temperature in ˚C.

$$\overline{E} = \frac{\overline{P}}{\sqrt{0.9 + \frac{\overline{P}^2}{[L(t)]^2}}} \qquad \textbf{(4)}$$

L (t) = 300 + 25t + 0.05t^3

According to the previous estimations, the mean annual precipitation of the study area is 813.36mm and the mean annual temperature is 22.33 C˚. Hence, the mean annual actual evapotranspiration is 733.26mm. The mean annual potential evapotranspiration is greater than the mean annual rainfall of the area.

3.4 Recharge and discharge

3.4.1 Recharge

Most groundwater originates as recharge in upland areas, water enter that infiltrates from precipitation on the ground surface. Some water enters the subsurface by seeping out of the bottom of surface waters, a situation more common in arid and semi- arid climates than in humid climates. In arid and semi-arid environments, the amount of recharge received by aquifers is far more critical to the sustainable use of water. Hence, in arid and semi- arid regions/ areas, selection of best accurate and suitable method of recharge estimation is crucial though it is not an easy task.

Recharge is addition of water to a groundwater reservoir. The main mode of recharge of the study area is downward flow of water through the saturated zone reaching the water table. The main sources of recharge that are assumed are rainfall and seepage from the intermittent rivers in the case of Raya valley and from intermittent and perennial rives in the other valley-Kobo valley. Hence, the recharge of the area is characterized as; areal and short term recharge as it occurs and over an area, from a line source such as ricers and covering a short period (months/years).

Since there are different sources and processes of recharge, estimation methods of recharge, which have their own limitation in applicability and reliability, are also many in number. The important recharge estimation methods applied for this study are: Water balance (WB) method and Chloride mass balance (CMB) method. The Cumulative Rainfall Departure (CRD) method establishes relationship between rainfall, abstraction and water level fluctuation. As there was not representative water table fluctuation data, it has was estimated the monthly groundwater table fluctuation of aquifers considering the estimated water requirement of crops and the current water consumption of the population.

3.4.1.1 Water balance (WB) method of recharge estimation

The water balance method states that the difference between the inflow and outflow is equal to the change in storage which is expressed by the equation:

In flows-Outflows = change in Storage

The sources of inflow of the study area are precipitation and seepage from the bottom of the available streams. The infiltrated rainwater or surface water (streams) outflows either as evapotranspiration or surface runoff. Though springs with insignificant discharge rate exist in the study area, they are not included in the water balance as their discharge rates have no effect on the groundwater (see section 3.4.2). The base flow component is also excluded due to lack of data on the base flow of Golina River, Which is the only perennial river in the study area. Therefore, assuming the change in storage is zero, the recharge amounts of the Raya and Kobo valleys are estimated only using precipitation, runoff and evapotranspiration and the above equation is simplified to:

$$I = P - Q - ET \qquad (5)$$

Where,

I= recharge amount,

Q= runoff and

ET= evapotranspiration.

From the previous calculation in section, 3.2.1.2 and 3.2.2 precipitation, runoff and evapotranspiration has been estimated. The annual precipitation estimated using Isoheytal is 813mm. As the study area is characterized by rough topography and the metrological stations are located in irregular space, the value of Isoheytal is more acceptable. The annual precipitations of the Raya Valley and Kobo Valley taking into consideration the total area of their basins are 2096.73MCM and 1098.57MCM. The calculated annual runoff of the Raya valley considering 14 catchments of streams that flow to the Raya valley is 268.71MCM. The value of annual runoff of the Kobo Valley considering the Golina River including Hormate and Kelekelit cachment is 61.8MCM.

The annual potential evapotranspiration of the study area from the vegetation cover is 1065mm and the annual actual evapotranspiration at annual average temperature 23.33C° is 733.26mm. As the value of potential evapotranspiration is over estimated, the value of actual evapotranspiration is more realistic.

Hence, the total annual actual evapotranspiration of the Raya Valley from the vegetation (AET), which covers 89% of the total area, including the evapotranspiration from the free water body - Ashega Lake (ETw), is 1698.11MCM. The value of the actual evapotranspiration from the vegetation of the Kobo Valley (AET) which covers 96% of the area is 951.18MCM.

Substituting all the values in the above formula:

$$R_R = P_R - Q_R - (AET_V + ET_W)$$

$$= 2096.73 - 268.71 - 1698.11\text{MCM}$$

$$= 129.91\text{MCM}$$

$$R_K = P_K - Q_R - AET_K$$

$$= 1098.57 - 61.8 - 951.18\text{MCM}$$

$$= 85.59\text{MCM}$$

The annual recharge of the Raya and Kobo valleys are 129.91 and 85.59MCM, respectively.

3.4.1.2 Chloride mass balance (CMB) method of recharge estimation

The chloride mass balance method is based on the assumption of conservation of mass between the input of atmospheric chloride and the chloride flux in the sub-surface. For steady state between the chloride flux at the surface and the chloride flux beneath an upper zone where evapotranspiration and mixing of rainfall and pore water takes place a site specific moisture flux can be calculated for the unsaturated zone by (as cited in Xu Y., 2003):

$$R_{sm} \times Cl_{sm} = P \times Cl_p + D \qquad (6)$$

Where,

Rsm = the moisture flux (mm/yr)

Cl_{sm} = chloride value in soil moisture (mg/l)

P = rainfall (mm/yr)

Cl_p = chloride value in rainfall (mg/l)

D = Dry chloride deposition (mg/m^2 yr)

The basic assumptions in this method are: there are no major change in chloride concentration occurred over concerned period due to external sources like fertilizers, weathering products and or evaporits. Substituting the $\mathbf{Cl_{sm}}$ in the above equation for the chloride concentration in groundwater at the water table (Cl_{gw}) gives the total recharge rate (R_T):

$$\mathbf{R_T \times Cl_{gw} = P_{eff} \times Cl_p + D} \qquad \mathbf{(7)}$$

Where,

R_T = areal total recharge

Cl_{gw} = the harmonic mean of chloride value in groundwater.

To compute the value of chloride in precipitation, four rainfall samples from Raya valley and four from Kobo valley were collected. Since the analytical result of the rainfall samples collected from Kobo area are over estimated may be due to improper analytical work , only the analytical result of the rainfall samples collected from Raya are used for the estimation of recharge using this method.

As result, the average chloride concentration of the rainfall is 1.8475mg/l.The value of harmonic mean of chloride concentration in the groundwater of Raya and Kobo study areas are 20.8 and 20.19mg/l (see appendix 7). The effective precipitations of the Raya and Kobo areas, which are calculated by subtracting surface runoff from precipitation, are 591.36 and 577.48mm, respectively.

Since the study area is far from coastal areas and there is no artificial source of chloride, the value of dry chloride deposition is assumed as zero. Substituting the above mentioned values, the total recharge of the Raya and Kobo study area are 52.48mm/year and 52.8mm/year respectively.

3.4.1.3 Cumulative rainfall departure method of recharge estimation

The cumulative rainfall departure method is used to estimate the water level fluctuation of the study areas as the areas have no representative data of water table fluctuation records. The method is applied taking into to account the estimated monthly groundwater consumption at household level and irrigation requirement of crops.

The CRD method is based on the premise that water level fluctuations are caused by rainfall events. The method is applied in unconfined aquifers where there is groundwater level fluctuation. In order to apply the method, monthly rainfall records, water levels, borehole abstractions and aquifer properties including specific yield, size of recharge area and natural outflow data important. Rainfall, water levels and abstraction rates must be representative for the recharge area of the aquifer. Recharge is calculated as (Xu Y., 2003):

$$\mathbf{R_T = S_y\left[\Delta h_i + \frac{(Q_{Pi} + Q_{outi})}{AS_y}\right]} \qquad \mathbf{(8)}$$

Where,
R_T = Total recharge

S_y = Specific yield

Δh_i = Water level change in month i

Q_{Pi} = Groundwater abstraction (L^3 / T)

Q_{outi} = Natural outflow (L^3 / T)

A = Effective Recharge area (L^2)

The cumulative rainfall departure method, which is used to estimate total recharge, was used to estimate the water table fluctuation of the Raya and Kobo areas. The annual recharge of the two areas was estimated using chloride mass balance (Section 3.4.1.2). Moreover, amount of groundwater which is used for domestic and irrigation purpose was estimated (Table 3.5). The effective recharge area of the two areas was estimated using Global Mapper7. The Raya Valley has an effective recharge of 1003Km^2 and the Kobo valley has 343Km^2 (see appendix 21). But, since the groundwater system is assumed as closed system, the natural outflow is taken as zero. As result, the water table fluctuation of the Raya area ranges between 132.9-194.1mm and it ranges between 468.34-480mm monthly in Kobo area (Fig.3.5 and 3.6) . The average monthly groundwater table fluctuation in the former area is 168.58mm and it is 475.49mm in the latter area (Table 3.5).

Table 3.5 Estimated monthly groundwater abstraction and water table fluctuations

	Monthly Irrigation requirements of crops of the study areas(MCM) and rainfall(mm)											
Valley	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Raya	18.91	16.76	8.28	3.46	5.404	14.07	12.82	6.94	11.47	4.7	6.77	15.21
Kobo	0.415	0.364	0.035	0	0.011	0.14	0.17	0.095	0.15	0.019	0.091	0.321
AMR	33.4	33.4	63.3	76.8	58.9	26.2	125	187.8	66.6	42	24	17.04
	Abstraction of both for crops and household water consumption o population of the areas, MCM											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Raya	19.04	16.89	8.4	3.59	5.54	14.2	12.95	7.07	11.6	4.83	6.9	15.34
Δh,mm	132.9	141.4	175	194.1	186.3	152.1	157	180.3	162.2	189.1	181	147.6
Kobo	0.44	0.38	0.06	0.02	0.03	0.16	0.19	0.12	0.17	0.04	0.11	0.34
Δh,mm	468.3	469.9	478.4	479.5	479.2	475.8	475	476.8	475.5	478.9	477.1	471

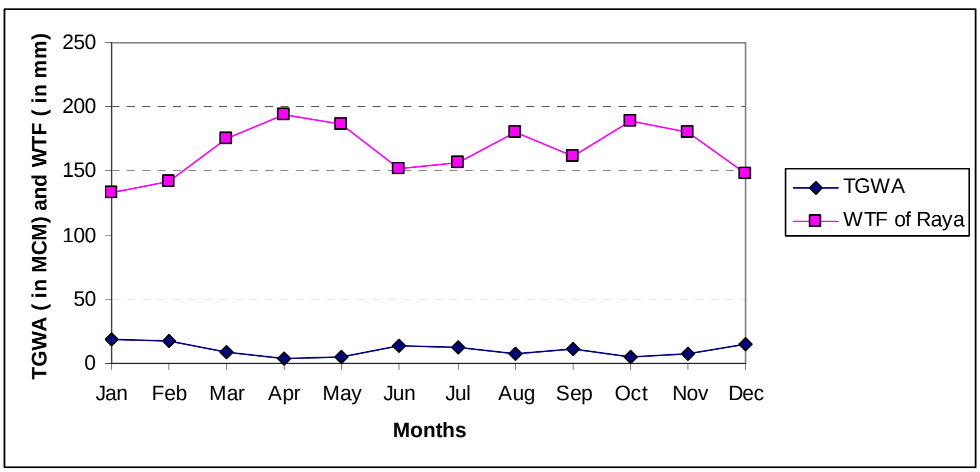
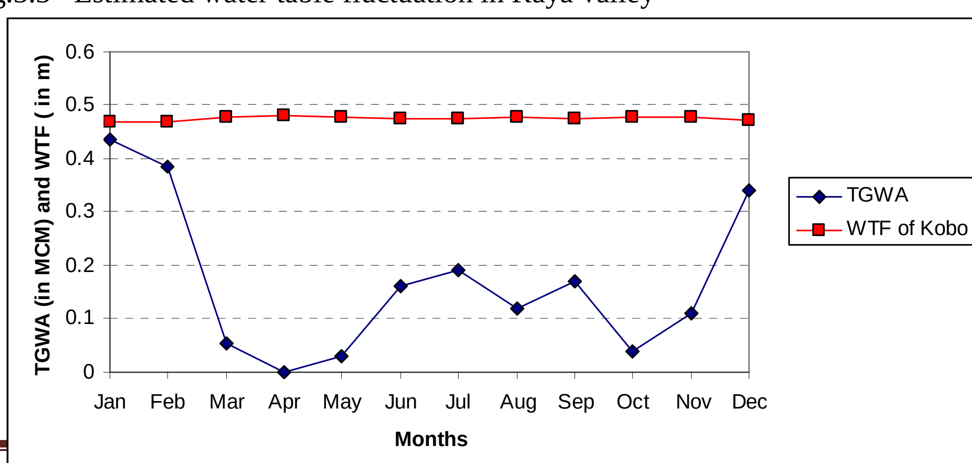
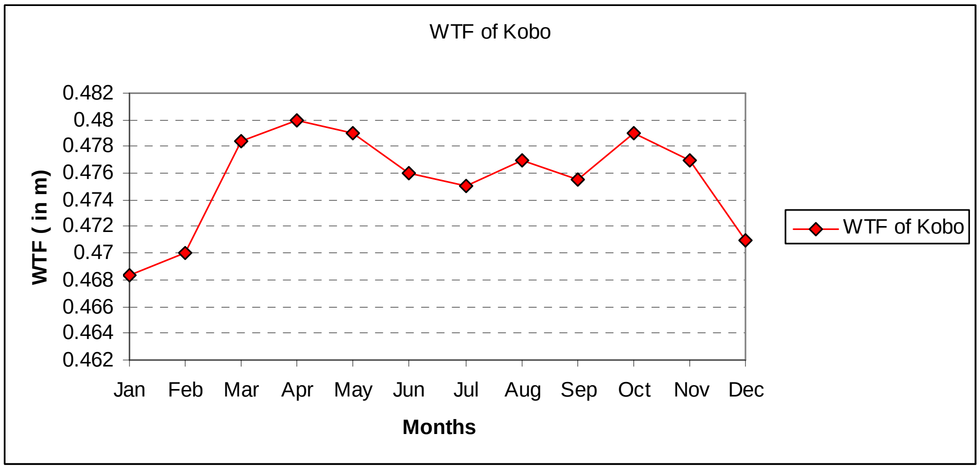


Fig.3.3 Estimated water table fluctuation in Raya valley



a)



b)

Fig.3.4 a) and b) Estimated water table fluctuation in Kobo Valley

3.4.2 Discharge

3.4.2.1 Natural springs

The natural discharges of the Raya area are the springs that are found in the western escarpments. These springs are used for water supply for the people who live in the near by location. For example, According to the inhabitants of the 'May-Hawas' at the foot of the hills of 'Gerakasu' (see Plate 3.2), the spring, which have an average discharge of 0.64-.14l/s, located at this area is used for unprotected water supply for 60-70 households that have an average four family size and the discharge of the springs decreases gradually during the dry seasons.

Plate 3.2 spring with discharge of 0.14 – 0.19l/s in western escarpment near Alamat area

The other spring of the western escarpment of the Raya area which is used for water supply and cleaning purpose is located at 'May-Alekety' near 'Shekomajo' town along the 'Bolty' stream with unknown discharge. Springs, owned by individuals, found on the Raya valley floor located Waja area are used for small irrigation purposes. The total discharge of 21 springs is $0.3m^3$. The discharge rate of these springs increase gradually increases from October Febrary and attains the minimum value in May (MOWR, 2008).

Springs found in the Kobo valley are also used for water supply.

During the field work, springs at Sheway Mareyam, Haroya Ameba, Aedeba and Tekelosh are visited and these springs are well developed and reservoirs are constructed (see Plate3.3).

Plate 3.3 Developed spring for water supply from the western escarpments of the Kobo area

According to the inhabitants, there is water taping program. The people are taping the water on average from 1 to 3 o'clock in the morning and from 9-11 o'clock in the afternoon. The discharge of these springs is unknown because their sources are covered with concerts and cement.

3.4.2.2 Boreholes

Based on agricultural extension workers of the Raya area, there are 106 wells in Raya Valley, out of these 50 wells are found in the Alamata sub-basin. One well has a capacity to irrigate 36ha. The total number of wells that irrigate currently in Raya-Azebo and Alamata area are 15 and 3 respectively. The total area irrigated in the former area is 530ha and in the latter area 108ha is irrigated. There are 13 wells in the Kobo Valley, 8 wells are found in Hormat-Golina to irrigate 295ha and 5 wells in Waja-Golisha area. The average discharge of the wells of the Raya Valley is 32.3l/s and that of the Kobo valley is 50l/s (Fig. 3.13)

3.4.3 Wetland

The wetland of the study is limited in some localities. During the field work, the wetland at Geregala area is encountered though the inhabitants of the Waja area confirm the existence of wetland at this area. It has been observed that birds were dependant on the wetland at Geregale area (see Plate 3.4 and 3.5).

Plate 3.4 Wetland near Garjale area

Plate 3.5 Birds dependant on the wet land near Garjale area

3.5 Crop water requirement (CWR) and Irrigation requirement.

The crop water requirement represents the rate of water used by the crops for their survival, favourable to good crop yield. It is important for development of water resources, planning of farm irrigation system and design of irrigation projects. Irrigation requirement is the quantity of water, which is artificially applied to the crops for their growth.

It doesn't include the water contributed by natural resources. The crop water requirement is mainly affected by: the type of crops, growth stages, climatic parameters, wind velocity, relative humidity, soil characteristics and available moisture content in the soil or available water supply to the field (Suresh, 2008). The estimation of crop water is carried out by determining the consumptive use (evapotranspiration) of the crop considering effective rainfall, crop factor (K) and reference evapotranspiration (ETo). The effective rainfall is part of rainfall which is effectively used by the plant to meet its consumptive need. Its value depends, among others, on the intensity of the rainfall. In the case of light rainfall, the entire rainfall may become effective, depending on the initial moisture content. But when the rainfall is heavy, only a fraction of it will be effective, as a substantial part of the rainfall is lost through run-off and deep percolation. The crop factor is the ratio between the consumptive rate and the rate of reference evapotranspiration, which is defined as the evapotranspiration rate from a reference surface such as a large uniform grass that is considered worldwide as the reference surface. The consumptive use or crop evapotranspiration under standard and no stress condition and irrigation requirement are computed using the CROPWAT8 software which requires data on: mean monthly minimum and maximum temperature, ˚C; Percentage sunshine duration, hours; wind speed, Km/s; effective rainfall, mm and relative humidity in percentage. Meteorological data and rainfall data collected from Kobo, Waja, Alamata, Mehoni Stations are used (Appendix 1-4). But other important data such as maximum effective rooting depth and soil water depletion fraction for no stress for the mentioned crops are adopted from (Suresh, 2008) due to data limitation. In addition to these meteorological data , the type of crops proposed by (MOWR,2008), the Cropping Pattern & operational calendar of the study area , the growth stage in days and the crop coefficient (K_c) of the initial , development, middle and late stage of the crops (Appendix 8,9 and 12) has been used for computing the water requirement of the crops.

According to (MOWR, 2008) agronomy report, Sorghum, Sesame, Cotton, Groundnut, Papaya, Orange, Coffee and Banana for wet season and Onion, Industrial tomato, pepper, Green beans, Papaya, Orange, Coffee and Banana for dry season are selected both for wet and dry season considering stakeholders' preference, food security, employment generation, increased household income, potential for expansion, agro-ecological suitability, foreign currency earning, yield potential and less water requirement.

The decade water requirement and irrigation requirement of all crops is estimated, except the perennial crops such as papaya, orange and banana (Appendix 13). Based on their cropping calendar, the total water requirement and irrigation requirement of the Sorghum, Cotton, Sesame, Green beans, Groundnut, Tomato, Onion, Pepper and Coffee is estimated under standard condition (Table 3.7).

Table 3.6 CWR and Irrigation requirement of crops.

S.N	Crop Type	CWR,mm	Peff,mm	Irr.Req,mm
1	Sorghum	706	358.8	350.4
2	Cotton	782.1	360.8	424.9
3	Sesame	602.7	313	286.5
4	Green beans	332	71.1	259.1
5	Groundnut	564.7	343.8	224.3
6	Tomato	570.1	114.3	455.1
7	Onion	534.9	121.5	412.2
8	Pepper	512.5	115.8	395.6
9	Coffee	2104.2	635.9	1515

Based on the crop water demand and irrigation requirement analysis and the total area coverage of each crops , which is proposed by MWOR, the total volume of water required by the crops for Raya and Kobo area (Table 3.8 and 3.9) was estimated which is used to evaluate the whether the number of existing wells drilled are enough or not. Hence, the total amount of water required for irrigation, from Raya study area is 127. 423MCM.

Table 3.7 volume of water required for irrigation in Kobo area

		Area-10%	Area-15%	Area-20%	Area-25%	Area-30%
		Area(ha) =51	Area(ha)=76	Area(ha)= 101	Area(ha)= 123	Area(ha)= 152
Crops	Irr.Req,mm	VWR,MCM	VWR.MCM	VWR.MCM	VWR.MCM	VWR.MCM
Sorghum	350.4	0.18*	0.27	0.35	0.43	0.53
Sesame	286.5	0.15	0.22	0.29*	0.35	0.44
Green beans	259.1	0.13*	0.2	0.26	0.32	0.39
Groundnut	224.3	0.11*	0.17	0.23	0.28	0.34
Tomato	455.1	0.23	0.35	0.46*	0.56	0.69
Onion	412.2	0.21	0.31	0.42	0.51*	0.63
Pepper	395.6	0.2*	0.3	0.4	0.49	0.6
	Total	1.21	1.82	2.41	2.94	3.62

* *Percentage coverage of crops proposed by the researcher to estimate annual irrigation requirement*

Table 3.8 Amount of water required for irrigation in MCM (Raya study area)

S.N	Crop Type	Area(ha)	Area (%)	CWR,mm	Irr.Req,mm	Required water for irrigation ,MCM
1	Sorghum	1,800	10	706	350.4	6.31
2	Cotton	4,500	25	782.1	424.9	19.121
3	Sesame	3,600	20	602.7	286.5	10.314
4	Green beans	1,800	10	332	259.1	4.664
5	Groundnut	1,800	10	564.7	224.3	4.04
6	Tomato	3,600	20	570.1	455.1	16.384
7	Onion	4,500	25	534.9	412.2	18.55
8	Pepper	1,800	10	512.5	395.6	7.13
9	Coffee	2,700	30	2104.2	1515	40.91
		26,100			TOTAL	127.423

During the field work and collection of data from the zonal agricultural administration, coffee and cotton are not the most common crops in the Kobo area. Therefore, their irrigation requirements are not included in this specific area. However, the total volume of water required for irrigation of the above crops, except coffee and cotton, of the Kobo study area is estimated considering the total area available for irrigation. The irrigable land of the Kobo valley, which consist of Waja-Golesha and Hormate- Golina is 507ha (KVDP manager). Assuming 10%, 15%, 20%, 25% and 30% irrigation area coverage of each crop of the Kobo Valley, the total irrigation requirement of the crops presented in the table below is estimated (see table 3.8).

Assuming the percentage area coverage of the crops of the Raya Valley, which is proposed by MOWR, and the Kobo Valley crops are the same; the total annual irrigation requirement of the crops of the above crops will be 1.88MCM.

CHAPTER FOUR

EVALUATION OF GROUNDWATER SUSTAINABILITY USING INDICATORS

4.1 Introduction

To evaluate the groundwater sustainability, indicators that are proposed by the Groundwater indicator working group (2007) are used. These are: Renewable groundwater resources per capita, total groundwater abstraction/ groundwater recharge, total groundwater abstraction / exploitable groundwater resources, groundwater as a percentage of total use of drinking groundwater, groundwater depletion, total exploitable non-renewable groundwater resources/annual abstraction of non renewable groundwater resource, groundwater vulnerability, groundwater quality , groundwater treatment requirement and dependence of agricultural population on groundwater.

According to the working group, the groundwater indicators: support sustainable groundwater management of groundwater resources, provide summery information about the present state and trends in groundwater system , help to analyzed the extent of natural processes and human impacts on groundwater and facilitate communication and public participation in groundwater resource planning. The indicators: help in the improvement of water resource management through better assessment of the water resource situation in a given hydrological, hydrogeological, provide for better mobilization of resource, act as important communication tool for managers and the public, establish effective communication between various groups of water users, describes the state of the resource and can be used for predicting the future condition of the resource.

Under this chapter, in order to evaluate the sustainability of the groundwater reserve of the study area the indicators shown in table 4.1 are used. Indicators such as total exploitable non-renewable groundwater resources/annual abstraction of non renewable groundwater resource, groundwater depletion, groundwater quality and groundwater treatment requirement are not used because the groundwater resource is not non –renewable, groundwater depletion is not observed during the field work and the groundwater quality no treatment.

Moreover, as the population is extremely dependant on the groundwater for drinking and agricultural practice the other indicators like groundwater as a percentage of total use of drinking groundwater and dependence of agricultural population on groundwater are not mentioned in detail. The selected indicators for this study need to be quantified. For example to quantify the total amount of renewable groundwater resource and total exploitable of the groundwater resource, the storativity, specific yield, specific coefficient must be determined. Evaluation of vulnerability, which is defined as the susceptibility of the saturated zone of the aquifer to being contaminated, of the groundwater of the study areas, needs the determination of the types of aquifers, the depth of their water table and transmissivity of the aquifers of the Raya-Kobo valley.

As the study area is characterized by absence of perennial streams, except at Kobo Valley, low and inconsistent rainfall occurrence and variable distribution the groundwater, it is obvious that the groundwater is important. Moreover, the inhabitants both in urban and rural depends on the available groundwater.

The urban population depends on the groundwater for water supply. The rural population depends on the groundwater for water supply and agricultural practice. Therefore, the sustainability of the groundwater is tested using the indicators listed in the table above.

Table 4.1 Sustainability indictors used for the study area

S.N	Sustainability indicators	Variables or components (see next sections)
1	Renewable GW resource x100/ inhabitants	See below
		Total population
2	Total GW abstractionx100/GW recharge	Total water use
		Annual recharge
3	Total GW abstractionx100/ exploitable GW resource	Total water use
		Exploitable amount of water
4	GW vulnerability	Soil property
		Unsaturated media and thickness
		Aquifer media
		Groundwater level below ground

4.2 Evaluation of groundwater Vulnerability variables

4.2.1 Hydrogeological units of aquifers

Identification and study of the hydrogeological units and characterization of these units is very crucial for the evaluation of variables of the groundwater vulnerability indicator of the study area. The study area comprises of two Hydrogeological units. These are volcanic rocks and alluvial deposits. The volcanic rocks, characterized as fractured and weathered, are found at the escarpments and plateau. During the field work from Almata - Maichew and from Kobo - Teklosh, it has been observed that springs with small discharge from these units have been used as water supply for small community. The alluvial deposit unit, which is the primary interest of this study which located at the valley, is the result of weathering and erosion of the volcanic rocks of the surrounding plateau. The size of the sediments and their thickness of the alluvial deposit are variable. The grain size is coarser towards the foot of the escarpments. At the center of the valley the size decreases and comprises intercalation of gravels, gravelly sands, silty sands, clay and silty clay. The thickness of the gravel and sand, which is more productive and used as water source for irrigation and water supply, increases towards the center of the valley (Fig 3.7).

4.2.2 Aquifer types and depth to water table

Study of the aquifer types and the depth of the static water table ensure the evaluation of the vulnerability of the groundwater to contamination and or to climate change. Considering this purpose, the VES of the previous works and most of the lithological logs have been studied and they revel that the aquifers are semi confined or unconfined type which are composed of gravels and sand. At some localities the aquifers consists of intercalation of variable finer sediment sizes with limited extent (Fig 3.7-3.12). Aquifers of the WF3 of The Waja-Golesh sub-basin consists of large amount of silt, clay and mixture of both at their top. The WF5 of the Kobo- Gerbi sub- basin is dominated by clay and silt. As result of this, the groundwater of this sub- basin is not productive. The average depth of the static water table in the various sub basins of the study area are summarized and described in the tables below.

Table 4.2 Aquifer thickness and static water table of Raya-Kobo study area.

S.N	Sub-basin	Well fields	AAT,m	SWL,m below ground surface
1	Mehoni	WF9/BH_{1-4}	?-116	21-30
2		WF13/BH_{1-5}	72-128	30-56
3	Alamata	WF4/BH_{1-3}	88-131	20-44
4		WF6/$BH_{1,3,4}$	72-94	25-32
5	Waja-Golesha	WF_{1-4}	100	17
6	Hormat-Golina	WF_{7-8}	87	22

AAT= range of average aquifer thickness, SWL= range of static water table, ASWT= average static water table.

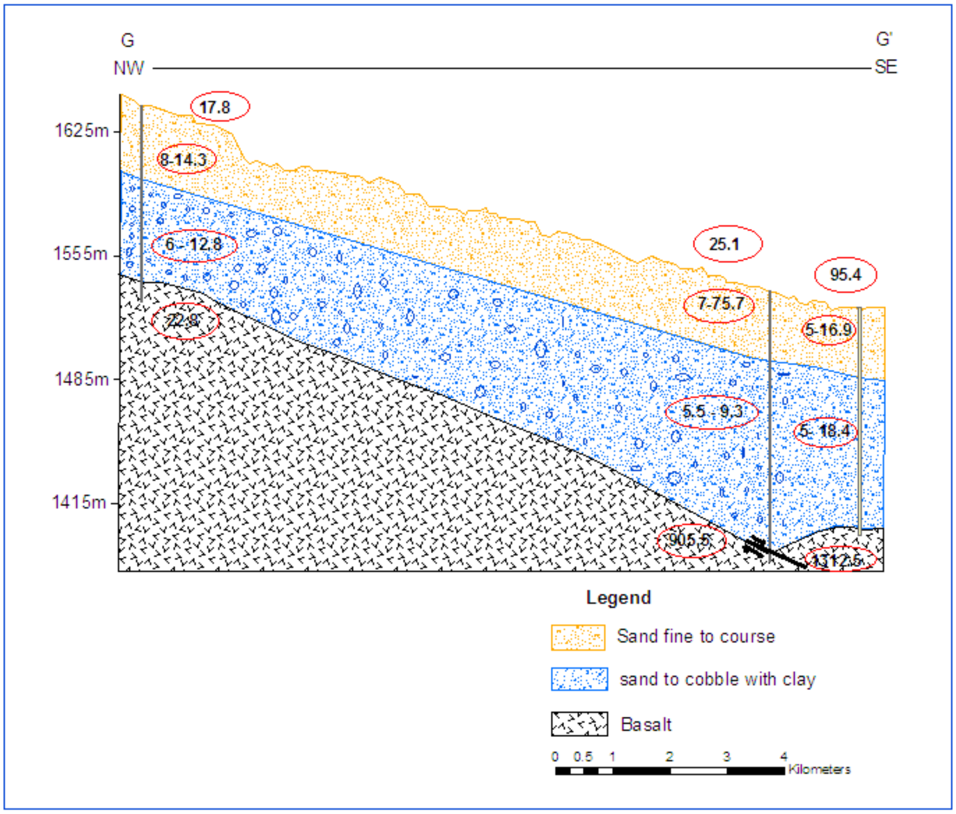


Fig. 3.5 Geo- electrical section NW-SE direction - Kukuftu area of Raya (Afework Hailu, 2010)

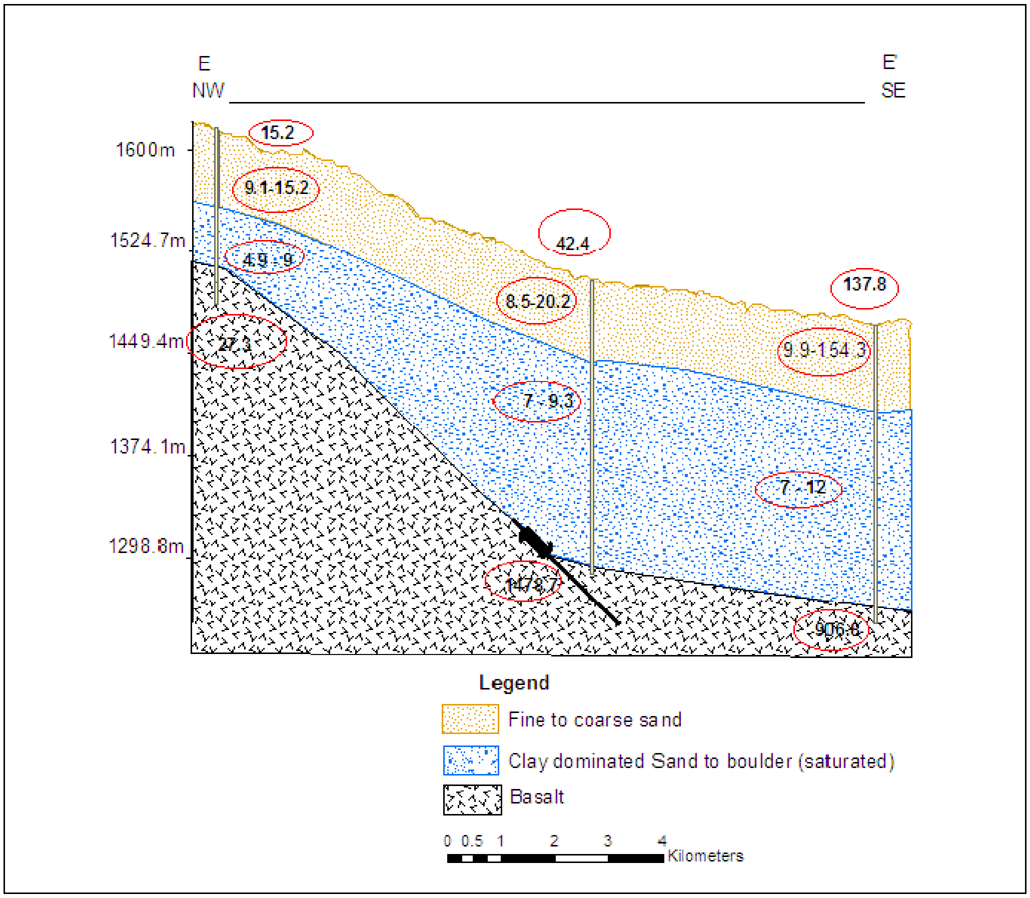


Fig. 3.6 Geo- electrical section NW-SE direction - Kara area of Raya (Afework Hailu, 2010)

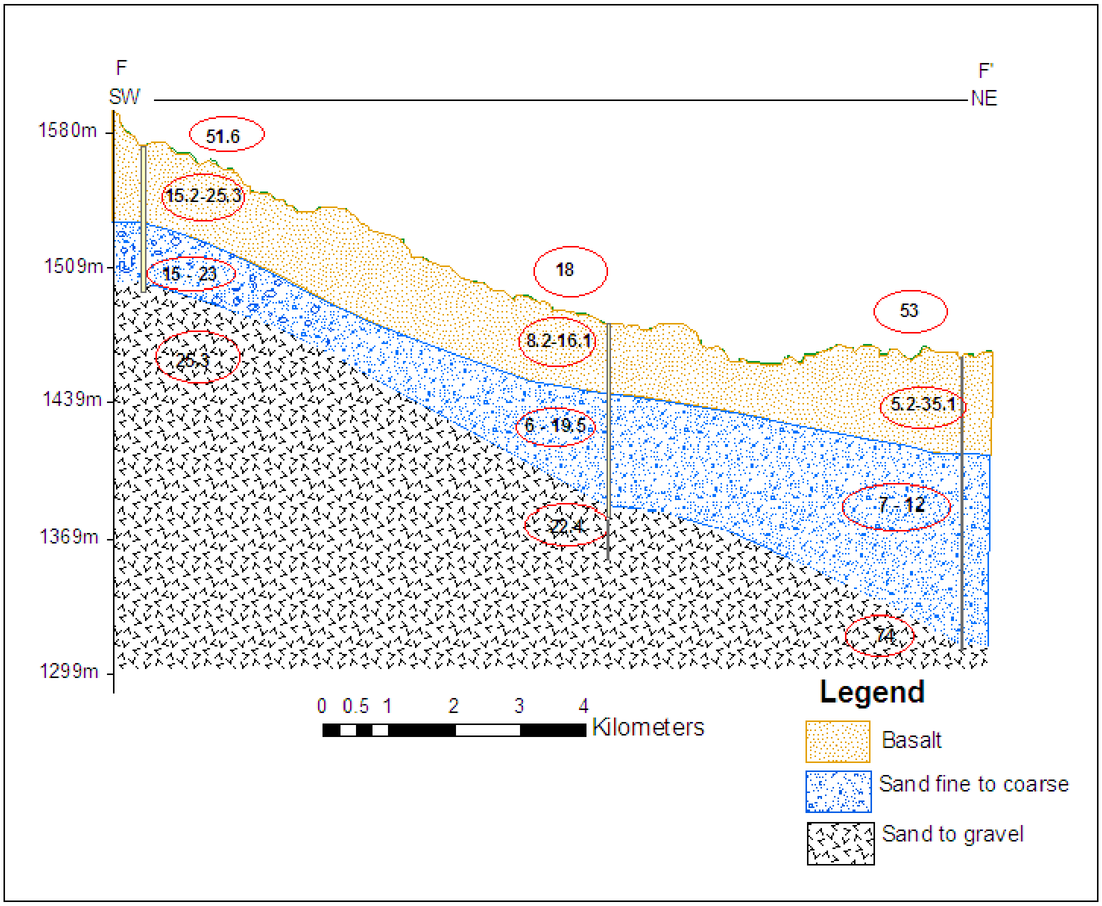


Fig. 3.7 Geo- electrical section NW-SE direction - Kukuftu area of Raya (Afework Hailu, 2010)

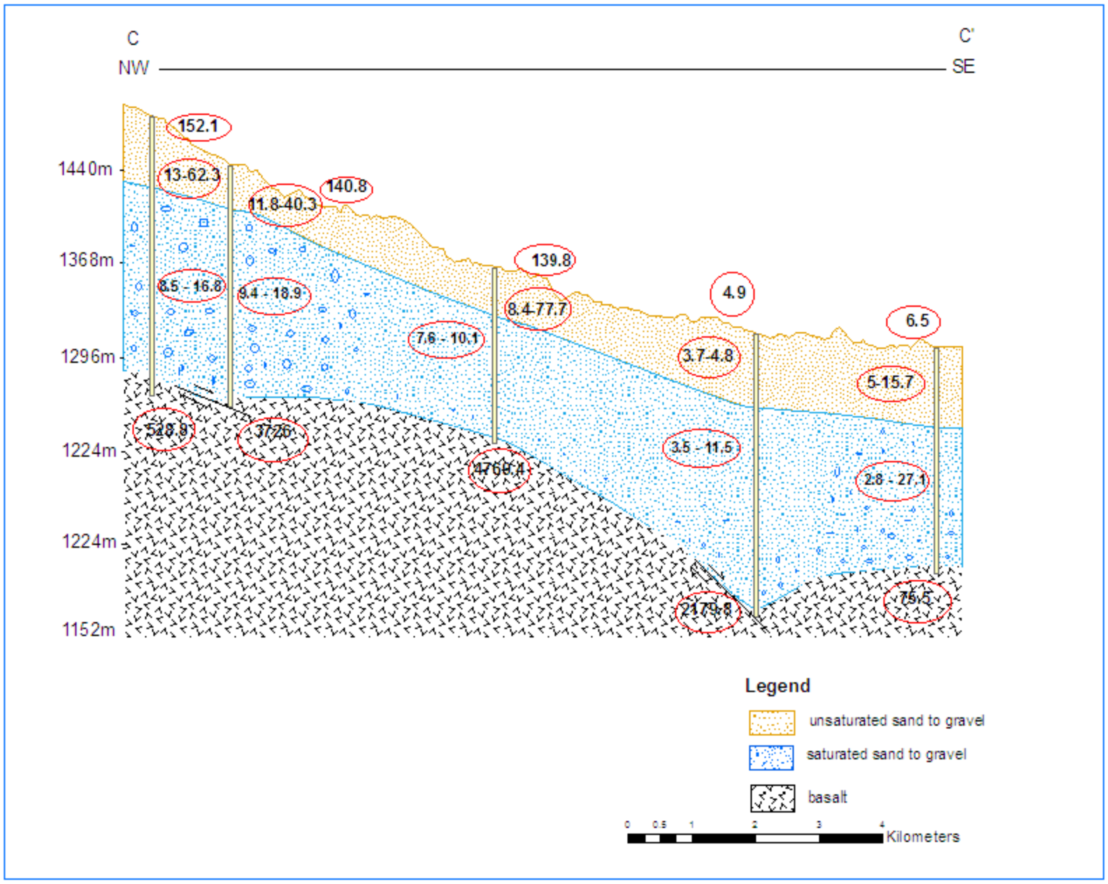


Fig. 3.8 Geo- electrical section NW-SE direction – Gerjele area of Raya (Afework Hailu, 2010)

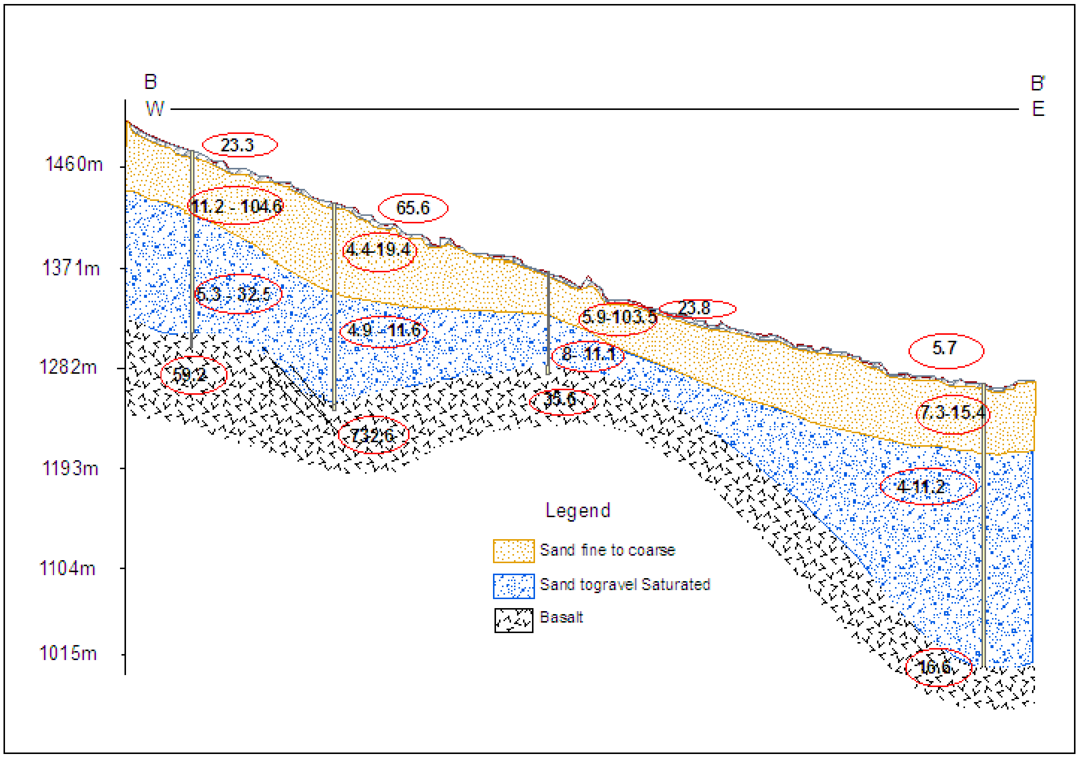


Fig. 3.9 Geo- electrical section NW-SE direction - Alamata area of Raya (Afework Hailu, 2010)

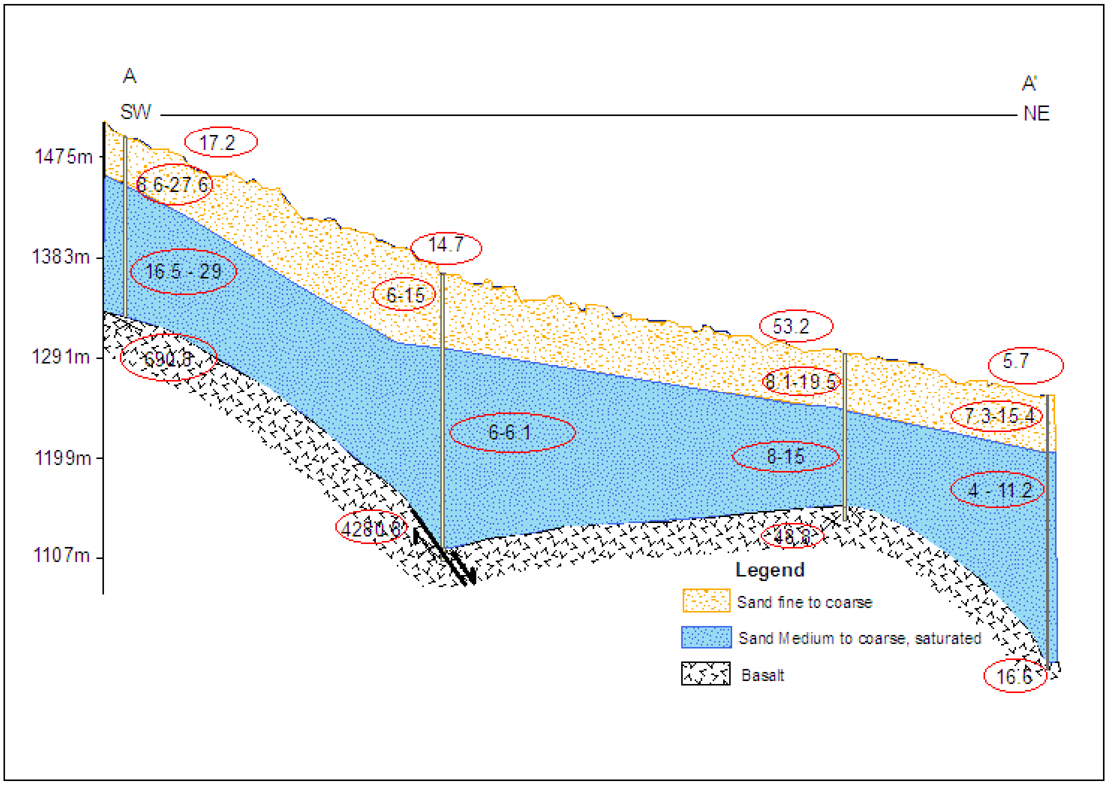


Fig. 3.10 Geo- electrical section NW-SE direction – Waja area of Raya (Afework Hailu, 2010)

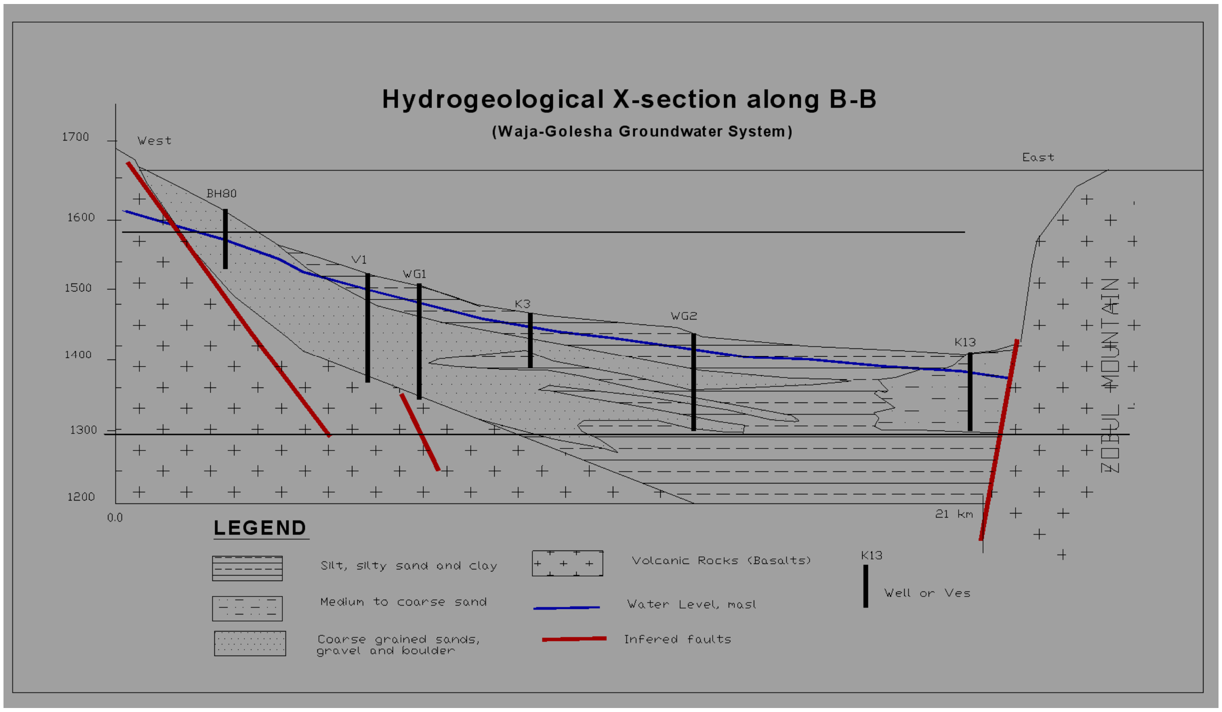


Fig. 3.11 Geo-electrical section E-W direction Waja –Golesha (MWOR and MCE, 2008)

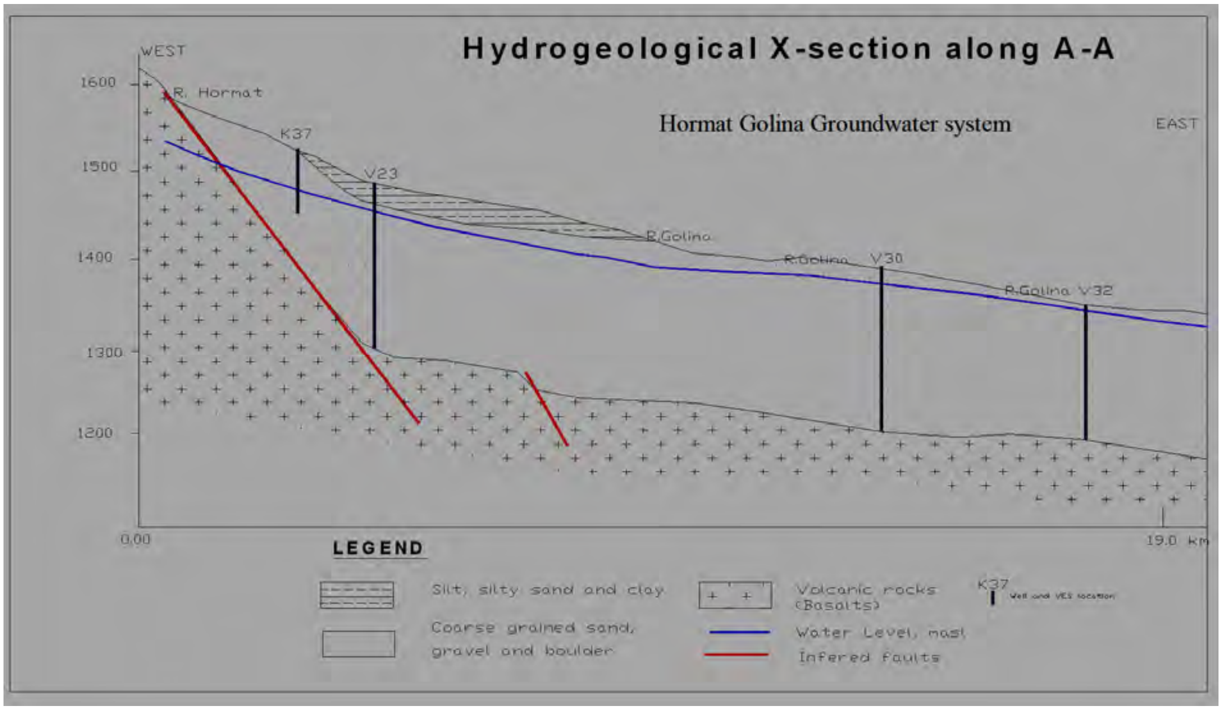


Fig.3.12 Geo-electrical section E-w direction Hormat –Golina (MOWR and MCE, 2008)

4.2.3 Hydraulic parameters of aquifers

The pump test performed in the Raya area using WF_4, WF_6, WF_9, WF_{13} , which consists of single pumping and 5 observation wells, reveals that the average transmissivity of the Mehoni and Alamata sub-basins are 1787, 545, 1435, 2304 m^2 / day respectively (MOWR and CECP,2008) with specific yield of the Raya area aquifers is 0.252. The pump test results conducted on Waja-Golesha and Hormat- Golina sub- basins was collected from the KVDP office. The report reveals that average transmissivity of these sub-basins are 546m^2 /d and 317m^2 /d respectively with specific yield of the Kobo area aquifers is 0.11. According to the aquifer potentiality classification of (as cited in Getachew Welamo, 2009), transmissivity greater than 500 and range 50 between 500 with the same unit are considered potentially high and moderate respectively. Hence, the aquifers of the Raya-Azebo and Waja- Golesha area are high and the Hormat- Golina is potentially moderate.

The cross sections of the study areas show that the lithologies of unsaturated zone are mainly dominated by sand and intercalation of sand, silt or clay. The western part of the valley is mainly characterized by sands. The central and the eastern part of the valley comprises of sand though at some location they are dominated by silt, clay or loam soil.

The aquifers are unconfined or semi-confined types which are lithologicaly composed of gravel sand and sand.

The vulnerability value of aquifers is estimated taking into account the above given information. The major features to evaluate the vulnerability value are; soil media, depth to water table, unsaturated zone and aquifer media. Based on the weighting and rating of these features (Table 4.3 and Appendix 19), the vulnerability value of the study area was estimated. The estimated value of the vulnerability indicator was 43.

Table 4.3 Estimated vulnerability value of the study area

S.N	features	Study area features	rating	weighting
1	Soil media	Thin or absent (western part of Valleys)/ clay (central and eastern part of the Valleys)	5/1	2
2	Depth to water table	20-60m	1	1
3	Unsaturated zone lithology	Sand	4	5
4	Aquifer media	Sand	4	3
	Total value	43 - 35		

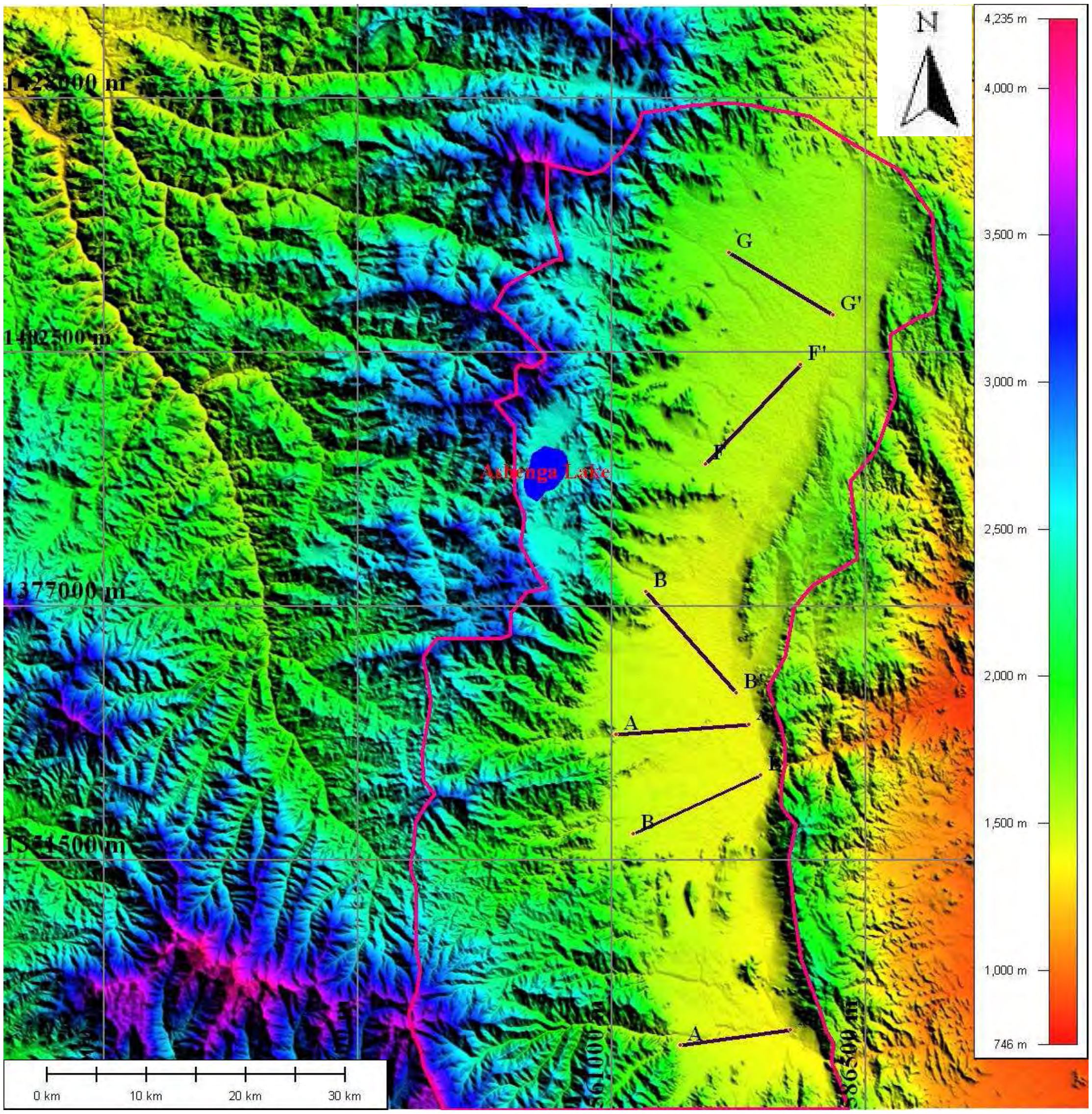


Fig 3. 13 Cross section lines of the Geo-electrical sections

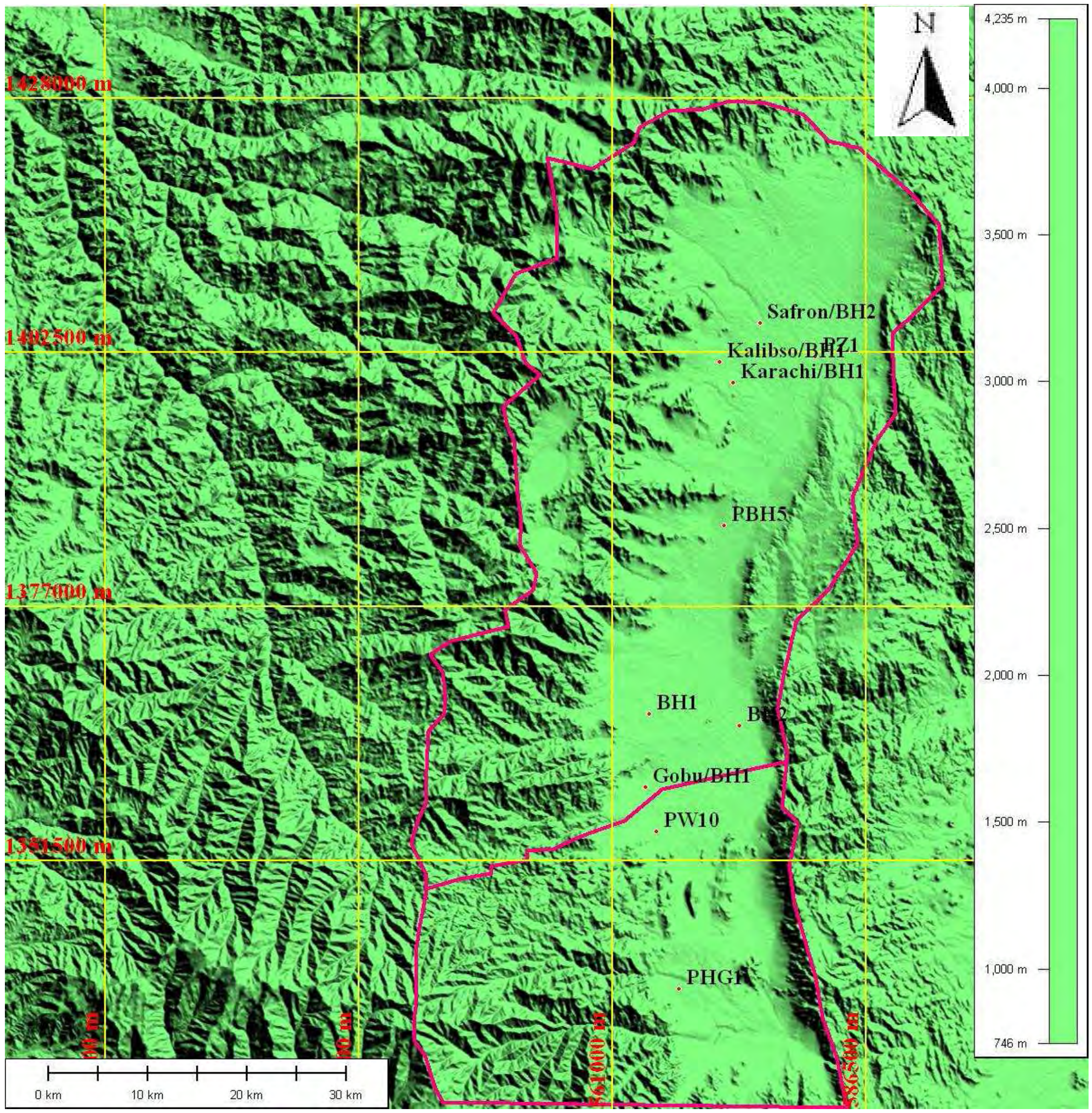


Fig 3. 14 Some of the wells with lithological log (Appendex 21)

Table 4.4 location , discharge, SWL of wells of the study area (MOWR,2008; MOWR and MCE,2008)

S.N	Sub basin	Name of well field	X,m UTM	Y,m UTM	Z,m Elevation	Discharge rate (l/s)	Static water table(SWL)
1	Mehoni	**WF_9/BH_3**	569798	1400023	1628	30	20.66
2	,,	**OB_1-90**	569708	1400022	1629		21.3
3	,,	**OB_2-90**	569799	1399934	1627		19.91
4	,,	**OB_3-90**	569888	1400024	1626		18.8
5	,,	**OB_4-135**	569933	1400026	1626		18.52
6	,,	**OB_5-205**	570007	1400025	1624		17.41
7	Mehoni	**WF_{13}/BH_5**	575406	1408290	1626	49.5	35.79
8	,,	**OB_1-90**	575316	1408290	1627		36.71
9	,,	**OB_2-90**	575407	1408200	1625		35.17
10	,,	**OB_3-95**	575501	1408289	1625		35.32
12	,,	**OB_4-135**	575541	1408288	1625		34.98
13	,,	**OB_5-205**	575611	1408286	1624		34.3
14	Alamata	**WF_4/BH_2**	565885	1378788	1458	49.7	19.73
15	,,	**OB_1-95**	565837	1378871	1460		20.11
16	,,	**OB_2-90**	565894	1378699	1459		19.49
17	,,	**OB_3-92**	565977	1378790	1458		20.78
18	,,	**OB_4-132**	566017	1378789	1457.65		20
19	,,	**OB_5-200**	566084	1378791	1456.65		19.24
20	Alamata	**WF_6/BH_3**	563156	1366192	1494	30	24.47
21	,,	**OB_1-90**	563066	1366192	1496		12.41
22	,,	**OB_2-90.44**	563153	1366101	1495		24.69
23	,,	**OB_3-89.2**	563245	1366190	1493		22.66
24	,,	**OB_4-129**	563286	1366192	1492		22.28
25	,,	**OB_5 - 198**	563355	1366195	1491.68		21.87
26	Hormat-Golina	**WF_7/HG_1**	568082	1338941	1478	51	20.6
27	,,	**WF_7/HG_2**	569450	1338823	1458	51	15.1
28	,,	**WF_7/HG_3**	569659	1338130	1451	20	21
29	,,	**WF_7/HG_4**	569354	1339493	1448	51	17.55
30	,,	**HG_5**	571782	1333845	1428	50	19.97
31	,,	**HG_6**	567804	1339909	1491	52	24.83
32	,,	**HG_7**	568283	1340339	1482	50	20.7
33	,,	**HG_8**	567346	1340010	1508	50	28.73
34	,,	**HG_9**	569905	1339618	1463	10	26.1
35	,,	**HG_{10}**	570348	1339366	1451	34	24.2
36	,,	**HG_{11}**	571055	1335915	1434	50	14.4
37	,,	**HG_{12}**	572295	1335804	1418	50	16.3
38	,,	**HG_{13}**	571683	1336365	1424	50	18.26
39	,,	**HG_{14}**	571067	1336466	1433	50	16.66
40	,,	**HG_{15}**	574997	1330600	1422	50	8
41	,,	**HG_{16}**	574865	1331232	1414	25	8.5
42	,,	**HG_{17}**	574673	1331879	1411	50	10.12
43	,,	**HG_{18}**	574474	1332360	1409	50	9.25

4.3 Estimation of amount of groundwater use for domestic and irrigation purpose

4.3.1 Domestic water demand based on Recent and forecasted population

4.3.1.1 Recent Population size

According to the recent report of population and housing census (2007), the population size of the Weredas, which benefit from the groundwater of the valley, are 136,039; 85,359 and 33,135 which are the population size of Raya-Azebo, Alamata and Kobo Weredas respectively. The total migrants in Raya valley are 38,209 and in Kobo valley there are 26,829. Out of the total migrants, 13,327 and 5333 migrants have one year and less residence time in the two study area. All in all the migration rate with one year and less in Raya and Kobo valleys are 17% and 12% respectively.

Table4.5 Population size used for estimating the domestic water demand

	1994	2007
Raya-Azebo-Wereda	87,638	136,039
Alamata-Wereda	93,659	85,359
Kobo (town)- Wereda	28,706	33,135

4.3.1.2 Forecasted Population size

The population forecasting was conducted using the data of the second and third population and housing census reports. Future population is predicted based on the birth, death and migration characteristics which are the main factors responsible for changes in population. These factors are influenced by social an economic conditions in various communities. The assumption during this prediction is that excessive birth rate will be reduced due to family planning, reduction of death rates due to advancement of medical facilities and control of infant mortalities and the last assumption is that the migration is insignificant as the livelihood of the farmers is improved due to the irrigation.

The geometric increase method is used as population forecasting method. The method is expressed as: $\mathbf{P_n = P_i\ [\,1+ r/100\,]^n}$ where, P_i = initial population (population at the end of last known census, P_n = future population after **n** decades and **r** = percentage growth rate which is assumed to be constant and can be estimated from the initial and final known population sizes (Garg, 2008)

Table 4.6 Present and Forecasted population

	1994	2007	2017	2027	Growth rate(r) used for forecasting
Raya-Azebo-Wereda	87,638	136,039	169,491	211,169	0.2459 (calculated)
Alamata-Wereda	93,659	85,359	87,493	89,680	2.5(as cited from PAHC,2007))
Kobo (town)- Wereda	28,706	33,135	35,600	38,249	0.0744(calculated)

4.3.2 Estimation of Water Consumption at Household level

The water consumption at household level of the study area is estimated considering only the Weredas such as the Raya- Azebo, Alamat and Kobo that have access to the groundwater of the valley though some people with shortage of water and live in the periphery of the valley are also geting water from the valley using heavy tankers (Plate 3.6).

Plate 3.6 water delivery for household (Hada-Alega area) - Raya valley

To estimate the quantity of water consumption at household level, identification of the type of water consumption is very crucial. The types of water consumption at household level are classified into four categories (White *et al* 1972; Thompson *et al* 2001): Ingestion use (hydration/drinking and cooking); Hygiene use (hand-washing, food-washing, bathing, flush toilet, and laundry); Amenity use (car-washing, lawn watering, and recreation) and Productive use (small scale brewing, animal watering, construction, and horticulture run by household level).

The estimation of the water consumption at house level only focuses on ingestion use and hygiene use. The quantity of water required at household level is dependant on the living standard of the community. To quantify the amount of water required, there must be a limit on the amount of daily water consumption. Though different countries and literatures have different limits on the minimum requirement of water consumption, the researcher has estimated the total amount of water required at household level using the limit of the WHO and UNICEF 2000.

According to WHO and UNICEF (2000), the generic requirement of water at household level is 20 liters per capita per day. Hence, total amount of water required yearly, which is used for ingestion and hygiene, at household level (HHL) is estimated assuming 100% of the present and forecasted population has access to the groundwater (see table 4.7) though the 83% (112,912), 87% (74,262) and 99%(32,804) of the Raya-Azebo, Alamata and Kobo area populations get clean water respectively (see table 4.6). Thus, the total volumes of water consumed at household level of the people who have access to clean water in the areas are: 0.824, 0.542 and 0.24MCM respectively.

Table 4.7 Estimated amount of water required (in MCM) annually for ingestion and hygiene considering 100% population size.

Year	**Population in %**	**Raya-Azebo Wereda**	**WR at HHL (MCM)**	**Alamata Wereda**	**WR at HHL (MCM)**	**Kobo Wereda**	**WR at HHL,MCM**
2007	100%	136,039	1	85,359	0.62	33,135	0.24
2017	100%	169,491	1.2	87,493	0.64	35,600	0.22
2027	100%	211,169	1.5	89,680	0.65	38,249	0.28

4.3.3 Groundwater Dependant Population

The some urban populations are not mainly engaged in farming activity though their domestic water supply is dependant on the available groundwater. On the other hand, majority of the rural population are dependant on the groundwater both for farming and domestic water supply due to absence of clean surface water (see plate 3.7).

Plate 3.7 Community cleaning water for domestic water supply at Alamata area

Since the study area is characterized by low and variable rainfall distribution and absence of perennial streams, except Hormat –Golina sub basin, which comprise Golina River that flows throughout the year, the populations are mainly dependant on the groundwater. In order to evaluate the degree of dependence of the populations on the groundwater, evaluation of the Scio-economy of the population is crucial. Hence, in the table below which is organized from the population and housing census 2007 of Ethiopia; the age group, the amount of economically active population, the amount of employed , the types of source of water supply of housing unit, the types of waste disposal of housing unit of the urban and rural populations and other characteristics are presented .

Housing unit is defined as a separate and independent place of abode, either intended for habitation or not intended for habitation but occupied as a living quarter by a household (population and housing cencus, 2007).

Table 4.8 Age group of the three Weredas of the study area

Age Group	Kobo Wereda		Rya-Azebo Wereda		Alamata Wereda	
	Urban	Rural	Urban	Rural	Urban	Rural
0-4	3,398	27,095	2,068	18,967	579	11,987
5-9	3,794	28,963	2,044	20,517	567	12,509
10-14	4,293	25,868	2,156	16,405	605	11,183
15-19	5,136	20,233	2,250	12,092	576	9,234
20-24	3,456	14,300	1,498	8,545	473	6,261
25-29	2,504	12,634	1,390	7,966	355	5,366
30-34	1,716	9,332	1,059	7,309	271	4,346
35-39	1,699	9,999	824	5,916	231	4,054
40-44	1,443	7,534	676	5,362	211	3,405
45-49	1,257	7,380	427	3,432	161	2,746
50-54	1,053	5,925	462	3,577	140	2,486
55-59	793	4,946	267	2,427	115	1,957
60-64	754	4,083	311	2,396	103	1,636
65-69	626	3,846	182	1,515	63	1,259
70-74	496	2,722	191	1,501	56	1,108
75-79	357	1,976	121	768	26	651
80-84	197	1,138	73	746	20	424
85-89	100	485	27	180	5	140
90-94	45	221	20	105	1	43
95+	25	137	10	88	5	45

Source: 2007 Ethiopia population and housing census.

The populations that live in the three weredas; Raya-Azebo, Alamata and Kobo are directly or indirectly dependant on the groundwater. Their urban and rural populations are dependant on the groundwater for household consumption and farming activities during shortage and absence of rainfall. The urban population size of the Weredas is 16,055; 4,563 and 33,135 respectively. Their rural population size is 119,814; 80,840 and 146,852 respectively. The number of households in the Raya-Azebo,Alamata is 32,360 and 25,531 respectively. The urban households of the Kobo Wereda are 9,398.

The numbers of housing unit of these weredas are 31,468; 20,106 and 9092 respectively. The average number of persons per housing unit in Raya-Azebo /town/-wereda, Alamata/town/-wereda and Kobo/ town/- wereda is 3.6, 3.7 and 3.6 respectively. Assuming the same average for the rural areas of Raya-Azebo and Alamata, populations that get clean water by taping inside their house, in private, in shared compound or outside their compound are 113,285 and 74,392 respectively. The urban populations of Kobo, who live in the valley and get clean water by the same means, are 32,731 (Table 4.8). Hence, 83%, 87% and 99% of the populations get clean water respectively. By the same assumption, out of the total population of the valley, 67,780 persons, which comprise, 61% of the Kobo-towen wereda, 19% of the Raya-Azebo wereda, 20% of the Alamata wereda, have improper dumping waste. Either they dump waste in rivers or behind their house units.

Table 4.9 Population characteristics of the study area.

	Kobo		**Raya-Azebo**		**Alamata**	
Descriptions	**Urban**	**Rural**	**Urban**	**Rural**	**Urban**	**Rural**
Housing units	9,092	43,016	4,443	27,025	1,252	18,854
No. of households	9,398		4,778	27,582	1,286	24,245
Economically active between age 10-75+	25,950	132,758	5,166	65,336	1,433	34,266
Economically inactive	15,339	60,240	6,801	14,994	1,984	22,078
Activity rate	40.9	54.6	43.2	81.3	41.9	60.8
Employed	8,270	71,397	3,957	62,723	1,180	33,244
Unemployed	2,341	1,121	1,207	2,612	252	1,021
Unemployed rate	22	2	23	4	18	3
Migrant 0 year length of residence	2,114	1,536	1,406	2,272	275	1,167
Migrant 1 year length of residence	914	764	731	1,178	137	574
Housing units constructed by concrete/ cement	5,500	3,096	0	213	13	123
Housing units by source of water						
Tap inside the house , in private ,in compound shared or outside compound	9,042	8,092	4,388	11,109	1,252	9,302
Protected well or spring	5	7,717	30	3,158	0	1,984
Unprotected well or spring	0	12,668	21	5,580	0	2,631
River/ lake / pond	45	14,539	5	7,178	0	4,938
Housing units with toilet facility	4,456	39,955	2,385	20,973	1,042	17,727
Housing units of towns with Bathing facility	8,575	-	4,187	-	1,196	-
Waste disposal of housing units						
Proper disposal by collection	146	165	1,989	99	20	66
Waste disposal behind the house unit	2,902	39,285	1,141	14,635	1,002	14,625
Waste disposal by dumping in a river	2,667	1,100	309	2,308	82	1,764
Waste disposal by burning / burring	3,347	2,336	999	9,071	148	2,200

Organized from Ethiopia's 2007 population and housing census.

The rural economy of the Raya valley is dominantly dependant on agriculture though the agricultural practice is very traditional and the living standard of the population is very low (REST, 1996). Generally, it can be said that the people are directly or indirectly dependant on the available groundwater as the lowland of the study area is affected by low and inconsistent rainfall distribution.

4.4 Estimation of variables of other indicators

4.4.1 Current Groundwater use/ abstraction

Based on the Ethiopia 2007 CSA Scio-economic report, the total annual volumes of clean water consumed at household level of the population of Raya-azebo, Alamata and Kobo Weredas without taking into consideration the migrants are 0.82, 0.54 and 0.24MCM respectively. The total migrants who have 0 and greater than 0 year residence time in the Raya (Raya and Almata weredas) and Kobo valleys (Kobo wereda) are 38,209 and 26,829 , respectively. But the total migrants who have 0 and 1 year residence time are 13,327 and 5,333 respectively. The average rate of migrants, who have 0 and 1 year residence time, in Raya –Azebo wereda is 9%. In Alamata and Kobo weredas the rate is 4% and 2.4% respectively. In Raya area the average rate of migrants with less or equal to one year residence time is 6.5% where as in Kobo the rate is 2.4%. Considering the migration, the total amount of water consumed by the migrants at household level are 0.0894MCM, 0.0249MCM and 0.0058MCM, respectively. Hence, the total annual water consumption at household level combing the migrations and the population will be 0.91, 0.565 and 0.246MCM, respectively.

The total abstraction of water for irrigation purpose depends on the capacity of one well to irrigate farm land. According to the agricultural extension workers of the Raya area, one well irrigates 36ha. The total numbers of productive wells that exist in Raya Valley are 106.The current total irrigated area using three wells in Alamata area is 108ha. Where as in Raya-Azebo, 530ha land is irrigated using 15 wells. The average discharge rate of the wells that are used for irrigation practice in Raya Valley is 32.3l/s or 2790.72m^3 /day (MOWR, 2008).

In Kobo Valley irrigation; in Hormate-Golina area, 8 wells with discharge rate of 50l/s (4320m^3 /day) used to irrigate total area of 295ha. In Waja-Golesha area, 5 wells with the same discharge rate are used to irrigate 212ha (KVDP manager).

Though there is no clear irrigation scheduling in the study areas, the farmlands are irrigated only in the dry season (i.e. Jan. - Jun.). During this season, only 25 days of each month and total of 1900 hours are used for irrigation. The wells are pumped in average for 13hours per day of the irrigation months. Therefore, the total annual abstractions of groundwater to irrigate the mentioned farmlands of the Raya-Azebo, Alamata, Hormate-Golina and Waja-Golesha 3.314, 0.663, 2.74 and 1.71MCM , respectively.

Table 4.10 Total annual abstraction of the study areas.

Valley	Location	Purpose of Abstraction		T.Abstraction, MCM
		Irrigation, MCM	HHC,MCM	
Raya	Raya-Azebo	3.314	0.91	5.452
	Alamata	0.663	0.565	
Kobo	Waja-Golesha	1.71	0.246	4.696
	Hormat-Golina	2.74		

4.4.2 Amount of Renewable and Exploitable Groundwater Resources

4.4.2.1 Renewable Groundwater Resource

Estimation of the renewable groundwater resource of the study area requires computation water that flow to (inflow) the basin and out of (outflow) the basin. Its value is found using the formula below.

GWRR= [Inflow] - [Outflow]

The main sources of water to the groundwater (inflow) of the two valleys are rainfall and infiltration from river beds. The groundwater outflows either as evapotranspiration or runoff through the major rivers namely Sulula and Golina. The Sulula River collects water from all catchments of the streams that originate from the western highlands and flow out of the Raya basin at eastern outlet.

The Golina River flows out of the Hormat-Golina sub-basin at the eastern outlet by collecting all surface runoff. The major infiltration from the river beds occurs during the rainy months; July and August. During the other months either there is no or there is little infiltration, which is insignificant. Total amount of infiltration from the rainfall and streams of the valleys is estimated using:

$$I = P - Q - ET$$

Where, I= infiltration (MCM)

P= precipitation (MCM)

Q= runoff MCM)

ET= evapotranpiration (MCM)

To compute the annual infiltration, evaporation from free water bodies of the valleys and from vegetation cover are included. The only open water body in the study area is Ashanga Lake. The total evaporation from this body is 15.05MCM (Dessie Nedaw, 2003). From the land use and land cover data; evapotranspiration of the Raya valley occurs on 89% of the total area and it covers 96% of the total Kobo Valley. Hence, the total recharge of the Raya Valley is 129.91MCM and that of the Kobo Valley is 85.59 MCM (Table 4.10).

Table 4.11 Renewable groundwater resource of the Raya-Kobo valley

S.N	Name of the valley	Area,Km^2	P,MCM	Q,MCM	AET,MCM	I,MCM
1	Raya valley	2579	2096.73	268.71	1683.06 (89% of the area) + ET from Ashenga= 15.05	129.91
2	Kobo valley	1351.25	1098.57	61.8	951.18 (96% of the area)	85.59

This indicates that the total renewable groundwater resource of the Raya and Kobo Valleys are 129.91 and 85.59MCM respectively. These amounts of groundwater can be used annually from the two valleys without affecting/ lowering the groundwater table.

4.4.2.2 Exploitable Groundwater Resource

Exploitable groundwater resource is the amount of water that can be abstracted annually from a given aquifer under the prevailing environmental condition.
Total exploitable groundwater resources of the Waja-Golesha and Hormat-Golina , Mehoni and Alamata sub basins is estimated using the formula:

Exploitable groundwater resource= $A \times S_y \times DL$ (10)

Where, A= the effective area for groundwater recharge, Km^2

S_y = specific yield

DL= Average water level decline in dry period, m

In chapter one it has been seen that the rainy seasons of the areas occur from March to April and from July to August. During the dry seasons, which occur in Oct – Feb and May-Jun, the average water level decline in Raya area is 0.565m and during this period the average decline in Kobo area is 1.66m (Table 3.6).

The effective area for groundwater recharge in Raya and Kobo areas are 1003 and 343 Km^2. The effective areas for recharge in the Raya and Kobo valleys are plain of the Valley. The areas were delineated using Global mapper 7 software.

Hence, substituting these values in to the above formula taking the specific yield of Raya area 0.252 and 0.11 for Kobo area, the amount of exploitable groundwater resource of the Raya and Kobo Valleys is 142.81MCM and 62.63MCM, respectively.

4.5 Estimation of indicators at groundwater abstraction with respect to Renewable and Exploitable Groundwater resources

4.5.1 Sustainability indicators at current groundwater abstraction

The accurate and suitable sustainability indicators proposed to study the groundwater of the Raya Valley, which comprise of the Raya-Azebo , Alamata and Kobo weredas with the population size of 136,039; 85,359; and 33,135, respectively, explain the degree of importance of the groundwater, current and future exploitation of groundwater and the degree of the vulnerability of the groundwater to contamination.

The previous sections explain estimation of the important components that are used either as numerator or denominator of the indicators. In this section the indicators are described as percentage (Table 4.12). Considering the population size described in the above, the sustainability indicters are determined at the total current abstraction of the two valleys. The annual abstraction of the Raya Valley is 5.452MCM and that of the Kobo Valley is 4.696MCM.

Table 4.12 Summery of the Sustainability indicators at current abstraction

S.N	Components of SI	Estimated value of factors	Sustainability indicator (SI) in percentage
1	**Renewable GWR**	In MCM	RGWR / Inhabitants
1.1	Raya Valley	129.91	+0.59 (Ml/person)
1.2	Kobo	85.59	+2.58 (Ml/person)
2	**GW recharge**	IN MCM	TGWAx100 / GWR
2.1	Raya Valley	129.91	4.123%
2.2	Kobo Valley	85.59	5.488%
3	**Exploitable groundwater resource**	In MCM	TGWAx100 / EGWR
3.1	Mehoni sub-basin	142.8	3.82%
3.2	Alamata sub-basin		
3.3	Hormate-Golina	62.63	7.5%
3.4	Waja-Golesha		

+ The unit of the SI is million litters per person, RGWR= renewable groundwater resource, TGW= total groundwater abstraction, GWR= groundwater recharge, EGWR= exploitable groundwater resource.

4.5.2 Sustainability indicators at estimated crops irrigation requirement and at domestic water consumptions

In the previous chapter irrigation water requirements of crops such as sorghum, cotton, sesame, green beans, groundnut, tomato onion and coffee that are proposed for Raya Valley has been estimated using CROPWAT 8 software. The total annual irrigation water requirement for the mentioned crops which grow through out the year in Raya Valley and Kobo Valley is 127.423MCM and 1.88MCM respectively. The total irrigation area of the above crops covers 26,100ha in Raya Valley and 507ha in the Kobo valley.

The water consumption at household level estimated in the previous section is taking in to consideration the persons who have access to clean water which was reported by the 2007 population and housing census. In this section, the water consumption at household level of the 100% population size (i.e. 113,039 of Raya-Azebo , 85,359 of Alamata and 33,135 of

Kobo wereda) of the areas and including the migrants with 0 and 1 year residence time is estimated.

The annual water consumption of the Raya-Azebo, Alamata and Kobo wereda at household level considering 100 % population size and migrants is 0.825, 0.623 and 0.242MCM respectively. The total annual groundwater abstractions including the mentioned migrants are 0.9144, 0.6479 and 0.2478MCM respectively. The total abstraction of the Raya Valley at the estimated irrigation requirement, 100% household water consumption and the rate of migrants with 0 and 1 year residence time are 128.99MCM. The abstraction of the Kobo valley at the same consideration will be 2.13MCM. The value of sustainability indicators of the two valleys based on these annual abstractions is presented below (Table 4.13).

Table 4.13 Value of sustainability indicators at estimated abstraction of water

S.N	Factors	Estimated value of factors	Sustainability indicator (SI) in percentage
1	**Renewable GWR**	In MCM	$\frac{RGWR}{Inhabitants}$
1.1	Raya Valley	129.91	0.59Ml/person
1.2	Kobo	85.59	2.58Ml/person
2	**GW recharge**	IN MCM	$\frac{TGWAx100}{GWR}$
2.1	Raya Valley	129.91	99.2%
2.2	Kobo Valley	85.59	2.489%
3	**Exploitable GWR**	In MCM	$\frac{TGWAx100}{EGWR}$
3.1	Mehoni sub-basin	142.8	90.3%
3.2	Alamata sub-basin		
3.3	Hormat-Golina	62.63	3.4%
3.4	Waja-Golesha		

RGWR= renewable groundwater resource, TGW= total groundwater abstraction,
GWR= groundwater recharge, EGWR= exploitable groundwater resource,

4.6 Safe yield of the groundwater systems of Raya and Kobo Valleys

Safe yield of groundwater basin is defined as the rate at which water can be withdrawn perennially under specified operating conditions without producing an undesired result. In the past the term safe yield, implying a fixed quantity of extractable water basically limited to the average annual basin recharge (Todd, 2007). In this study, safe yield as management concept is estimated using the estimation from Naik and Awashthi(2003):

$$\textbf{Safe Yield} = Q_{ed} + Q_{dom} + Q_{ir} + Q_{si} \qquad \textbf{(11)}$$

Where:

Q_{ed} = Exploitable dynamic groundwater reserve, Mm^3

Q_{dom} = Volume of water used for domestic use in rainy season, Mm^3

Q_{ir} = Recharge due to irrigation returns, Mm^3

Q_{si} = Sewage infiltration, Mm^3 (if treated water is available)

From the previous estimations, the exploitable dynamic groundwaters of the two valleys are 142.8 and 62.63MCM respectively. To evaluate the volume of water used for domestic use in rainy season, the temporal rainfall distribution of the study area is considered. In chapter one it has been seen that the rainy seasons of the areas occur from March to April and from July to August. Taking the domestic water consumption 20l/person/day (previous assumption) and 100% of population size, the volume of water used for domestic use in rainy season of the Raya and Kobo Valley is 0.6 and 0.08MCM respectively. Since the value of recharge due to irrigation returns and sewage infiltration are unknown, they are taken as zero. Therefore, safe yield of Raya and Kobo Valley are:

$$(\text{Safe Yield})_{RV} = Q_{ed} + Q_{dom}$$
$$= 142.8\text{MCM} + 0.6\text{MCM}$$
$$= 143.4\text{ MCM}$$

$$(\text{Safe Yield})_{KV} = Q_{ed} + Q_{dom}$$
$$= 62.63\text{MCM} + 0.08\text{MCM}$$
$$= 62.71\text{MCM}$$

CHAPTER FIVE

RESULT AND DISCUSSION

In this chapter the result of the study will be presented and discussed. The out comes of the study such as the average annual temperature, the average annual precipitation, the total runoff of the study areas, the Actual and potential evapotranspiration, the total annual recharge, the renewable and exploitable groundwater resources, crop water requirements, safe yield and total area which is suspected to be source of contamination will be presented under section 5.1. The most important outcomes of this study ; values of sustainability indicators tested at the current and estimated groundwater use / abstraction for irrigation and domestic uses are also presented under section 5.2.

5.1 Result

5.1.1 Values of variables of groundwater sustainability indicators

The average annual temperature of the study area is 23.33C˚. Its average annual precipitation is 813mm. the total runoff of the Raya Valley, which comprises of 14 unguaged streams, is 268.71MCM. The result of the potential evapotranspiration is 1065mm and the value of the actual evapotranspiration is 733.26mm.

The total annual irrigation requirements of the crops, which are proposed by ministry of water resource, of the Raya Valley are 127.423MCM. The total annual irrigation requirements of the Kobo Valley considering the percentage coverage of crops proposed by researcher, is 1.88MCM. The total annual abstraction of groundwater from the Raya and Kobo areas groundwater systems which is used for irrigation , domestic water consumption of 100% population size and migrants who have one year residence tine domestic water consumption is 128.89 and 2.13MCM respectively.

The expected mean monthly water table fluctuation ranges from 0.133 to 0.194m in Raya valley. In Kobo valley it ranges from 0.468 to 0 480m. The average water level decline during the dry season is 0.565m and 1.66m in Raya and Kobo valley respectively. The total annual recharge of the Raya Valley considering 89% of vegetation cover is 129.9MCM. The Kobo Valley has a total of annual recharge taking into consideration 96% of vegetation cover is 85.59MCM.

Moreover, it was found that the annual recharge of the Raya and Kobo valley are 52.48mm/year and 52.8mm/year respectively.

The average exploitable groundwater resource of the Raya and Kobo areas aquifers is 143 and 62.63MCM respectively. The safe yield of the Raya and Kobo valleys groundwater systems 143.4 is and 62.71 MCM respectively.

5.1.2 Values of sustainability indicators

The sustainability indicators that show the available groundwater resource per person per year, the groundwater exploitation/ abstraction are estimated and evaluated at the current and estimated abstraction of groundwater in Raya and Kobo valleys. But the indicator of groundwater (intrinsic) vulnerability is evaluated considering the total basin that includes Raya – Kobo farmlands.

5.1.2.1 Indicator of available groundwater resource per capita

The total groundwater resource available at aquifer level in Raya valley is 0.59 million litters per person per year. The groundwater resource available in Kobo valley, only considering the Kobo wereda urban population is 2.58 million litters per person per year.

5.1.2.2 Indicators at current and estimated Groundwater abstraction / exploitation

The value of the abstraction indicator of Raya valley, which evaluates the current abstraction of groundwater with respect to the total annual recharge, is 4.12%. The value of this indicator in Kobo valley is 5.488%. The value of other abstraction indicator, which is estimated with respect to the exploitable resource, in Raya valley and Kobo valley are 3.82% and 7.5% respectively.

In Raya valley the value of the abstraction indicator, which is evaluated considering the total groundwater required for irrigation, 100% population size and migrants who have one year residence time with respect to annual recharge of the valley, is 99.2%. The value of the same indicator in Kobo valley but estimated only considering 100% population size of the urban population, migrants with one year residence time and irrigation requirement of crops is 24.89%.

The values of other abstraction sustainability indicator of Raya valley and Kobo valley which considers the exploitable resource and the estimated required groundwater resource are 90.3% and 3.4% respectively.

5.1.2.3 Indicator of groundwater(intrinsic)vulnerability

The value of groundwater vulnerability indicator is estimated taking into account the soil thickness and presence, unsaturated and aquifer media and depth of water table. Therefore, the value of the indicator is 43.

5.2 Discussion

The study area comprises of Mehoni, Alamata, Waja-Golesha and Hormat-Golina sub-basin. The Mehoni and Alamata sub- basins are located in Raya valley. The Raya valley consists of the Raya-Azebo wereda and Alamata wereda. The Waja- Golesha and Hormate-Golina are found in Kobo valley. The Kobo valley comprises of the Kobo wereda. The inhabitants of these weredas live on the floor of the valley, except the rural population of the Kobo wereda. Therefore, the inhabitants of these weredas are taken into account for the estimation of some of the components of sustainability indicators. Before discussing the results of sustainability indicators and their components, which are presented in section 5.3.2, the discussion of the results of precipitation, evapotranspiration, recharge and runoff are presented in section 5.3.1.

5.2.1 Precipitation, Evapotranspiration, Recharge and Runoff.

The monthly and annual precipitation of the Raya and Kobo catchments estimated based on the patched rainfall records of the Kobo , Waja, Alamata, Korem , Maichew , Mehoni , Chercher and Zoble stations.

The estimation methods of average precipitation applied are; Thiesson polygon and Isohytal methods. These methods are convenient because the topography of the study area is mountainous, the stations are not uniformly distributed and the rainfall distributions is affected by orography. But, the value obtained by the isohytal method, which is more convenient, is used in the estimation of total runoff and recharge in the water balance method. The average annual precipitation of the total study area is computed by this method is 813mm.

The potential evapotranpiration of the study area is 1065mm, which is computed using the Thornthwait method. The actual evapotranspiration of the study area is 733.26mm, which is estimated at 23.33 C° average annual temperatures using the Turc,Langberin, Wundit method. Since the value of the potential evapotranpiration is over estimated, the value of actual evapotranspiration is used in estimating the total recharge using the water balance method.

The Raya and Kobo catchments consist of streams that flow to the valley floor in the W-E direction. The Kobo catchment consists of Hormat, Kelekelit and Golina. The average annual discharge of the Golina River, which is Perennial River with a total catchment area of 262 sq.km, is 61.8MCM. The Hormat and Kelekelit are intermittent streams that join the Golina River in the floor of the valley. The perennial river has an outlet at the eastern escarpment. The major streams that are found in Raya cathment are Tirke + ulaula, Dayu, Hara, Ttengago, Oda, Harosha, Mersa, Gobu, Habro, Guguf, Fokisa, Haya, Werabeyi and Beyra.. These streams are intermittent and join the Sulula River which has an outlet at the eastern escarpment.

The total annual runoff of the Raya catchment taking into account the discharge of the 14 streams estimated Appling regionalization method is 268.71MCM. The total annual runoff of the Raya catchment estimated by Dessi Nedaw, (2003) and MOWR, (2008) are 60MCM and 114MCM, respectively. The value estimated by Dessi Nedaw is under estimated and the paper doesn’t give any information how the estimation is made and how many streams are considered. The value computed by MoWR, which was also described in the paper, is under estimated, excluded the discharge of Gobu and Mersa and only consider 10 streams of the Raya Valley also the annual surface runoff of Golina River taken by the MoWR was 38.8MCM. But, this research considered 14 streams of Raya Valley and the surface runoff of the Golina River is 68.1MCM.

The total annual recharges of the Raya and Kobo catchments are estimated using; the water balance and chlorine mass balance methods. The water balance method is used assuming the inflow is equal to the outflow. The method reveals that the total annual recharge of the two catchments is 129.91 and 85.59MCM respectively. The report of REST, 1996 describes that the total annual recharge of the Raya cactchment is 130MCM which was estimated using the same method. This value is almost the same as the estimation of this paper. According to Dessi Nedaw, (2003), the total annual recharge of the same area is 129.3MCM which is estimated using the same method. This result deviates from the results of this paper and REST, 1996. The total annual recharge estimated by this paper is used to evaluate groundwater sustainability indicators and their components, which are presents in the section below. In addition to this, the recharges of the catchment of the two study areas were estimated using chloride mass balance (CMB). The result shows that the total annual recharge of the Raya valley is 52.48mm/year and that of the Kobo valley is 52.8mm/year.

5.2.2 Sustainability indicators and their variables

To evaluate the sustainability of the groundwater of the study area, four sustainability indicators are used (see Appendix 15). Out of the ten groundwater sustainability indicators proposed by UNCEF only four are selected due to the available and collected data. The components of these indicators are; renewable groundwater resource/ total recharge, total inhabitants of the study area, total groundwater abstraction, exploitable groundwater resource and total area suspected to be source of contamination. The result of the total groundwater abstraction, exploitable groundwater resource and total area suspected to be source of contamination and the result of the sustainability indicators are discussed.

The result of the total annual groundwater abstraction of the Raya valley and Kobo valley includes the current annual groundwater consumption taking into consideration the population that has access to clean water and the current groundwater use for irrigation practice. The main purposes of the groundwater abstraction that are considered in the estimation of the indicators are; water consumption at household level and irrigation requirements of crops.

The total water consumption of the inhabitants at household level is calculated using the per capita demand proposed by the WHO and UNICF (2000) which is 20 litters per day pr person.

The total estimated people who have access to clean water currently in the Raya-Azebo, Alamata and Kobo weredas are 113,285 (83%) ,74,392(87%) and 32,731(99%), respectively. The total amount of groundwater abstracted from the study areas considers: the current population size that has access to clean water, assuming 100% population size will have access to clean water and taking into account the rate of migrants who have 0 and 1 year residence time. Hence, the total amount of groundwater abstraction of the Raya-Azebo, Alamata wereda and Kobo weredas, which are found in the study areas are 0.91, 0.565 and 0.246MCM, respectively. The total amounts of groundwater abstractions from the Raya and Kobo that are used for the current irrigation practice are 3.977 and 4.45MCM, respectively.

But, the total amount of groundwater abstractions, which should be used for the irrigation practice taking into consideration the types of crops and their area coverage proposed by the ministry of water resource, are 127.423 and 1.88MCM respectively.

Among the crops that were proposed by the ministry of water resource; tomato, onion, green beans, pepper, groundnut and coffee to grow during the dry season and sorghum, cotton, sesame, groundnut and coffee crops during wet seasons in Raya valley are used for the estimation of irrigation requirements. Theses crops are selected during the estimation due to the availability of their crop coefficient.

To estimate the irrigation requirement of crops that grow in the Kobo valley, identification of the types of crops and their area coverage is paramount importance. The total amount of groundwater that should be abstracted from the Kobo valley is estimated assuming all types of crops and the area coverage proposed in Raya valley, except coffee and cotton. The total estimated annual groundwater abstraction of the Kobo valley doesn't include the rural inhabitants of the valley as most of them are found out of the valley. Hence, the calculation is made only assuming the urban population of the area. Therefore, the total estimated amount of groundwater that should be used annually for domestic and irrigation in the Raya and Kobo valley are 128.89MCMand 2.13MCM respectively.

Before discussing the result of Exploitable groundwater resource, presenting the result of groundwater fluctuation is important. In Raya Valley, the estimated water table decline upon the estimated abstraction of groundwater during the dry periods from October to February and from May to Jun is 0.792m and 0.338m respectively. The average water table decline during the dry season in Raya is 0.565m. Whereas, in Kobo Valley the water table decline upon the estimated ground water abstraction during the same dry seasons is 2.365m and 0.955m respectively. The average water table decline is in Kobo area is 1.66m. The water table fluctuation was estimated using the total monthly abstraction of groundwater (see table 3.5). To calculate the total exploitable groundwater resource, the estimated average groundwater table declines that occur during the dry season, effective recharge area and specific yield of the aquifers are used. The effective recharge areas of the study areas are the total catchments of the two valleys.

Therefore, the exploitable groundwater resource of the Raya and Kobo catchments are 142.8MCM and 62.63MCM respectively. According to the report of REST, 1996, the exploitable groundwater resource of the Raya area was estimated as 130MCM. This amount is equal to the estimated amount of the annual recharge of the study area.

The cross sections of the study areas reveal that the lithology of the unsaturated zone of the aquifers of the study areas is sands or intercalation of sand and silts. The aquifer parameters indicate that the transmissivity of the aquifers of the study areas ranges from high to moderate. The soil media is thin though it is loam, clay or silt. The depths of the water tables range from 20m to 60m. The lithology of the unsaturated zone and aquifer media is sand. The vulnerability value of aquifers is estimated after identifying the following features; soil media, depth to water table, unsaturated zone and aquifer media (see appendix). Each feature has its own weight and rating and finally the total value of the vulnerability is calculated and the degree of vulnerability evaluated based on the classification. According to Groundwater indicators working group (2007), the classification are vulnerable at 35– 40, moderately vulnerable at 40–45 and highly vulnerable in parts where the indicator value is 45 or above. The parts where the indicator value is less than 35 can be considered to have low vulnerability. According to the above collected information, the calculated vulnerability value of the study area is 43.

Having discussed the results of the components of the indicators, the results of the sustainability indicators that are selected for the study areas are presented and discussed below.

The total groundwater resource available at aquifer level in Raya valley is 0.59 million litters per person per year. The groundwater resource available in Kobo valley, only considering the Kobo wereda urban population is 2.58 million litters per person per year. The results shows that 0.59 million litters per person per year and 2.58 million litters per person per year is the available groundwater that can be used for domestic water supply for irrigation and other purposes annually. From the results it can be seen that as the population size increases the available groundwater resource decreases. As this indicator is important for planning purpose, the abstraction of the groundwater resource should consider the value of the available groundwater resource for each person in the catchments.

The value of the abstraction indicator of Raya valley, which evaluates the current abstraction of groundwater with respect to the total annual recharge, is 4.12%. The value of this indicator in Kobo valley is 5.488%.

In Raya valley the value of the abstraction indicator, which is evaluated considering the total groundwater required for irrigation, 100% population size and migrants who have one year residence time with respect to annual recharge of the valley, is 99.2%. The value of the same indicator in Kobo valley but estimated only considering 100% population size of the urban population, migrants with one year residence time and irrigation requirement of crops is 24.89%.

The value of other abstraction indicator, which is estimates the current abstraction with respect to the exploitable resource, in Raya valley and Kobo valley are 3.82% and 7.5% respectively. The values of abstraction sustainability indicator of Raya valley and Kobo valley which tested the estimated abstraction of groundwater for proposed irrigation and domestic water supply for 100% population and migrants with respect to the exploitable groundwater resource are 90.3% and 3.4% respectively.

The result of the indicator evaluated at the current abstraction of groundwater reveals that the current groundwater use for irrigation and domestic purpose in the Raya and Kobo areas are below 50% of the total exploitable ground water resources. Hence, at the stage current groundwater use the groundwater consumption is sustainable and it is under exploitation.

But, in Raya area, when the proposed irrigation practice (i.e. 26,100ha land is irrigated using groundwater for the proposed crops) and water supply for 100% of the population size is implemented, the groundwater use will reach at unsustainable and over exploitation stage. Whereas, in Kobo valley, when 507ha land is irrigated using the groundwater for the crops that are used by the researcher for the estimation and water supply for the 100% population of Kobo area is implemented, the groundwater use will reach at sustainable and the groundwater resource will be under exploitation stage.

The groundwater vulnerability indicator estimating approaches considers the presence and thickness of soil in the area, the depth of the water table and media of the unsaturated zone and aquifers. To estimate the value of vulnerability, weighting and ratings are given to these features (Table 4.3).The vulnerability value estimated ranges from 35 to 43%. This value of groundwater (intrinsic) vulnerability indicator reveals that it ranges from moderately vulnerable to vulnerable.

CHAPTER SIX

CONCLUSION AND RECOMMENDATIONS

The general objective of this study was to asses the quantity of the groundwater potential and to evaluate whether the domestic, irrigation demand can be supported sustainability. In addition to this, the study had specifically aimed at: evaluating the groundwater table fluctuation, quantifying the amount of the recharge of the precipitation, assessing the current and future water demand of the inhabitants, estimating exploitable groundwater resource and the safe yield of the aquifers and evaluating the degree of vulnerability of the groundwater.

In order to achieve the mentioned objectives sustainability indicators are used. The sustainability indicators that are used to evaluated the groundwater of the Raya and Kobo areas are; indicator of available annual groundwater resource per capita, indicators of groundwater exploitation and indicator of groundwater vulnerability. The available groundwater resource per capita is computed by dividing the total renewable resource of the catchment by the total inhabitants. One of the exploitation indicators is evaluated and computed by dividing the total groundwater abstraction by the total recharge. The other exploitation indicator is computed by dividing the total groundwater abstraction by total exploitable groundwater resource. The groundwater vulnerability indicator is evaluated considering the soil media, depth to water table, lithology of unsaturated zone and aquifer media.

6.1 Conclusions

Evaluating the groundwater sustainability indicators upon the current and estimated groundwater abstraction, the following conclusions have been drawn from the result of the study:

- The available groundwater resource of the study areas can support the total inhabitants as domestic water supply.

- Current groundwater abstraction for domestic water supply and irrigation practice in the Raya and Kobo Valleys is sustainable as the irrigation practices are being implemented in limited area. The groundwater resource is under exploitation.

- The estimated groundwater use for domestic water supply of 100% population and irrigation practice (26,100ha land) in Raya Valley will not be sustainable as the proposed total irrigable area covers large part of the valley. The groundwater resource will reach over exploitation stage.

- In Kobo area the estimated groundwater use for irrigation (507ha land) and 100% population domestic water supply will be sustainable as the irrigation area is limited in extent. And the resource will reach under exploitation stage.

- The groundwater of the study areas range from moderately vulnerable to vulnerable. The groundwater found in the western parts of the valley floor is moderately vulnerable. The groundwater found at central and eastern parts of the valley are relatively less vulnerable.

6.2 Recommendations

Based on the results and conclusions of the study, the following recommendations have been made:

- Since the available groundwater resource is sufficient for domestic water supply, concerned governmental and nongovernmental bodies should maximize and supply water for 100% population size.
- The current irrigation practice using groundwater is very low in both Raya and Kobo Valleys. Hence, the current irrigation practice using groundwater should be maximized.
- When the types of crops and area coverage (i.e. 26,100ha) proposed by ministry of water resource are implemented in Raya area, the groundwater may reach unsustainable stage. To increase the sustainability of the groundwater additional artificial recharge at the foot of the mountains should be implemented. In addition to this, to increase natural recharge, the current water shade- management should be enhanced.
- Since the current and estimated groundwater use in Kobo area is under development, concerned governmental and nongovernmental bodies should work hard to maximize the area coverage farmlands and implement irrigation practice using groundwater.
- Application of fertilizers during the irrigation practice may affect groundwater quality, to protect the groundwater from contamination the farmlands that are found western part of the valleys should use natural fertilizers. When fertilizers are implemented regular water quality test should be made.
- During the settlements of inhabitants, urban planers should consider and give consideration to the waste disposal site and protect the groundwater from contamination of the waste material. To protect the groundwater contamination from waste disposal of the inhabitants, concerned bodies should develop proper waste disposal mechanism and vulnerability map should be developed.

Limitation of the study

The limitation of the study are: representative data of water table fluctuation in both of the Valleys, record of surface runoff of the steams that are found in the area, record of groundwater that flow out of the catchments, base flow of the Golina River and aerial extent of aquifers. Therefore, effective record of water table fluctuation, record of natural outflow of the boundary condition, and record of base flow of the Golina River and aerial extent of aquifers will solve problems and will make the sustainable groundwater development and management complete and effective.

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Appendix

Appendix 1. Mean monthly minimum and maximum temperatures from stations.

Name of station	type	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	mean
Korem	Min	8.9	7.7	8.8	10.3	10.2	11.1	12.3	11.8	10.2	8.8	8	7.8	10
	Max	20.6	21.1	22.3	22.8	23.4	24	23.1	22.7	23.2	21.9	21	20.8	22
	Mean	14.7	14.4	15.5	16.7	16.9	17.5	17.7	17.3	16.7	14.7	15	14.5	16
Alamata	Min	12.9	13.6	15	16.3	17.3	18	17.7	16.8	15.8	15.2	14	13.1	15
	Max	26.8	27.7	29.1	29.7	31.7	33.9	31.7	30.6	30.8	30.1	29	27.7	30
	Mean	20.5	20.9	22.2	23.2	24.4	25.9	24.9	23.8	23.3	22.6	21	20.4	23
Maichew	Min	6	6.9	8.6	9.6	9.6	11.2	11.9	11.5	8.9	6.4	6.1	5.5	9
	Max	22	22.6	23.6	23.9	25.6	26.4	23.6	23.6	24	22.7	22	21.4	23
	Mean	14	14.8	16.1	16.7	17.7	18.8	17.8	17.6	16.5	14.6	14	13.8	16
Kobo	Min	12.5	13.7	15.6	16.3	16.5	17.8	18	17	15.6	14	12	11.5	15
	Max	25.6	26.6	28.6	29.8	31.2	33.3	31.7	30	29.8	28.5	27	25.9	29
	Mean	19	20.1	22.1	23	23.9	25.5	24.7	23.5	22.7	21.2	20	18.7	22
Waja*	Min**	8.8	12.6	13.8	15.4	13.6	15.4	17.7	16.9	15.3	12.1	7.7	8.7	13
	Max**	27.4	28	30.4	32	33	34.8	34.3	31.5	32	30.5	29	30.5	31
	Mean	18.5	20.4	22	22.4	23.6	25.1	25.6	24	22.5	21.2	20	20.1	22
Chercher	Min	13.3	13.6	15	16	16.9	19	16.7	16.1	16.3	15.1	14	12.5	15
	Max	24	24.7	26.3	27.9	29.7	32.6	30.2	28.4	28.4	27.5	26	24.8	28
	Mean	18.7	19.1	20.7	22	23.3	25.8	23.5	22.3	22.3	21.2	20	18.7	21
Mehoni*	Min	11.8	12.8	12.3	12.7	13.6	13.9	13.9	13.1	11.8	12.6	13	11.9	13
	Max	28.1	29.1	30.2	30.4	29.2	30.2	29.5	26.8	28	28.3	29	28	29
	Mean	19.9	20.5	20.4	20.9	21.6	22.8	22.2	20.9	20.7	20.7	21	20	21

Appendix 2 Patched sunshine duration (hours)
2.1 Patched sunshine duration of Kobo stations

year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	MASSD
1976	7.8	6.5	8.4	8	9.2	8.2	5.6	7.1	7.6	8.4	6.4	6.9	90.1
1977	5.5	7.1	8.8	8.9	8	7.4	6.4	6.5	6.9	8.7	8.7	8.4	91.3
1978	9.1	7.4	8.1	9.3	9.8	5.5	4.2	7.1	6.6	8.4	8.4	7.9	91.8
1979	5.4	8.4	7.4	8.8	7.6	6.8	7.1	6.2	7.8	8.5	9.9	8.3	92.2
1980	7.9	7.2	8.1	9.1	9	7.2	5.8	6.5	6.8	8.7	8.8	9.1	94.2
1981	9	9.1	8.7	6.8	8.3	6.2	6.4	7	7	9.5	9.4	8.5	95.9
1982	6.1	5.2	8.2	7.5	8.5	7.9	5.2	4.6	5.6	8.1	8.6	7.5	83
1983	7.2	8.9	6	7.9	7.1	5.6	5.4	7.2	7.3	9.4	9	8.7	89.7
1984	8.8	10	9.2	10.4	5.1	5.6	7.3	5.9	6.7	9.8	9.3	8.3	96.4
1985	9.4	8.5	8.9	7	7.8	7.6	7.5	3.6	4.7	8.6	10	7.8	91.4
1986	9.5	6.8	5.3	6.6	9.3	4.8	4.1	4.6	5.7	8	10	7.8	82.5
1987	8.3	7.5	5	7.5	5.6	5.6	7	6.7	7.7	9.3	10	8.3	88.5
1988	7.6	6.4	9.3	7.7	9.4	6	3.3	5.4	5.7	7.2	9.9	9.5	87.4
1989	9.2	6.3	7.3	7.1	9.6	6.2	5.6	6.6	7.6	8.1	6.7	5.9	86.2
1990	4.2	9.3	4	7.1	7.2	5.9	6.3	7.3	6.8	8.7	10.3	8.9	86
1991	9.4	7.5	9.5	8.7	10	7.1	4.8	6.7	5.8	8.8	9.5	8.1	95.9
1992	5.9	8.8	8.6	9.5	8.4	8.2	6	7.1	5.9	8.9	7.3	8.5	93.1
1993	8.6	8	9.4	7.4	9	7.3	6.4	5.8	5.8	8.2	9.1	7.4	92.4
1994	9.8	9.2	8.2	9.3	7.8	5.9	7.4	6.1	7.7	8.7	9.9	9	99
1995	9.8	8	9.5	7.8	9.2	7.6	4.9	7.1	7.9	8.6	9.8	8.7	98.9
1996	6.8	5.3	7.9	9.6	9.9	8.5	4	5.1	6.8	9.6	9.9	8.8	92.2
1997	8	7.3	9.3	6.9	9.4	6.2	3.1	5.1	7.3	9.5	9.7	8.1	89.9
1998	6.3	7.5	8.9	9.5	9.2	6.8	6.7	7.4	6	7.1	9	7	91.4
1999	6.9	4.4	8.7	6.6	9.1	6.3	6.1	6.5	7	9.6	10.1	9.3	90.6
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	86
2001	8	7.4	8.9	7.9	9.8	8.3	3.4	6.6	7.1	7.9	8.1	7.9	91.3
2002	7.8	8.6	8.7	9.7	6.5	5.7	4	5.8	7.7	8.9	9.1	8.5	91
2003	8.7	10.2	8.1	9	6.8	6.4	8.3	7.1	6.7	7.3	8.6	9	96.2
2004	8.1	8.7	9	6.8	7.2	6.1	7.3	5.6	6.2	8.1	9.9	9.4	92.4
MSSD	7.9	7.68	8.05	8.14	8.38	6.6	5.68	6.19	6.67	8.58	9.13	8.28	91.27

2.2. Patched sunshine duration of Maichew stations

year	Jan	Feb	Mar	Apr	May	Jun	Jul	Agu	Sep	Oct	Nov	Dec	
1976	7.2	9.6	8.4	9.9	8.7	7.5	3.8	4.3	8	8.4	7.8	7.6	91.2
1977	6.4	6.1	7.4	7.3	8.7	6.8	4.7	4.5	7.8	7.7	8.6	8.2	84.2
1978	6.6	7.5	5.8	7.3	8.1	9.1	4.4	4.5	7.5	8.5	8.7	6.6	84.6
1979	5.5	6.2	7.3	10.6	9	7.2	5.3	5.2	7.7	7.7	8.4	7.7	87.8
1980	8.1	8.8	4.7	9.8	9.5	6.4	5.2	5.1	7.2	7.9	6.3	6.9	85.9
1981	7.5	9.8	5.4	8.1	9.1	6.6	4.7	4.7	7.3	7.2	7.4	4.4	82.2
1982	2.3	6.6	9.4	9.8	9	7.4	5.7	5.9	7	8.2	9.4	8.6	89.3
1983	7.4	6.8	9.8	10.8	9.2	6.7	4.2	4.4	7.5	6.8	7.7	9.1	90.4
1984	8.9	9.4	8.5	10.6	10.2	5.6	5.5	5.3	6.8	6.4	7.5	7.6	92.3
1985	4.3	8	6.2	5	8.2	7.1	5	6	5.8	7.5	9.1	8.4	80.6
1986	7	7.6	8	8.9	9.7	6.4	6.1	6.3	6.4	8.6	9.4	8.9	93.3
1987	9.2	9.2	5.9	6.4	9.3	5.8	5.2	5	7.1	6.9	9	8.7	87.7
1988	7.8	10	8.8	10	9	6.5	5.7	5.6	6.8	9.1	9.1	8.4	96.8
1989	7.3	7.1	8.7	9.6	8.1	7.7	4.5	5	7.2	8.2	8.5	8.6	90.5
1990	5.5	6.8	13.8	11	9.7	5.7	4.2	4.3	7.2	7.1	8.9	9.4	93.6
1991	8.3	11.1	4.6	4	7.2	10	5.1	5.1	6.7	7.3	7.6	7.6	84.8
1992	6.2	6.9	7.5	9.7	9.3	8.2	5	4.8	6.6	6.5	5.3	5.4	81.4
1993	5.1	5.6	8.3	5.5	8	7.5	5.1	5.3	6.6	7.1	9	8.8	81.9
1994	8.9	8.3	6.4	10.3	9.9	6.3	4.6	5	8.3	8.7	7.6	8.7	93
1995	8.8	6.6	7	7.3	8.2	9.4	4.4	4.9	7.7	8.2	8.8	6.7	88
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	84.2
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	83.4
1998	5.2	6.3	7.4	8.7	8.7	6.9	4.2	4.3	7.3	8.5	9	9.3	85.8
1999	7.4	9.8	7.2	10.2	9.7	7.3	3.9	4.9	7	6	8.9	7.7	90
2000	9	9.8	9.7	7.3	9.2	6.3	5.2	5.5	5.9	7.1	7.8	6.3	89.1
2001	4.4	7.9	4.4	6.2	7.2	12	4.6	5	7	7.9	6.9	8.3	81.9
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	90.3
2003	6.4	8	6.3	9.9	9	6	4.7	4.4	7.3	9.4	8	7.9	87.3
2004	6.9	8	8.6	7.6	10.5	5.9	5.2	5.4	6.3	8	8.3	7.4	88.1
MSSD	6.9	8.01	7.41	8.49	8.89	7.2	4.95	5.13	7.06	7.64	8.08	7.78	87.57

Appendix 3. Wind speed (m/s) above 2m of the ground

3.1. Patched wind speed (m/s) Kobo station

year	Jan	Feb	Mar	Apr	May	Jun	Jul	Agu	Sep	Oct	Nov	Dec	MAWS
1976	1.8	2.1	2.1	2.1	1.6	2.6	2.3	2	1.7	1.8	1.8	2.1	24
1977	2.6	2.6	2.3	2.1	1.6	2	2.2	1.5	1	1.2	1.4	1.5	22
1978	1.7	2	2	1.7	1.6	1.9	1.6	1.2	1.1	1.3	1.8	1.7	19.6
1979	1.8	1.9	2.2	1.8	1.6	1.7	1.8	1.3	0.9	1	1.2	1.5	18.7
1980	1.7	1.6	1.6	1.5	1.3	1.4	1	1	0.1	0	0	0.1	11.3
1981	1.5	1.8	1.8	1.6	1.8	1.1	1	0.8	0.6	0.8	0.9	1	14.7
1982	1.7	2.2	2.1	1.3	1	0.9	1	0.8	0.7	0.7	1.2	1.8	15.4
1983	1.8	2.2	2.3	2.1	1.8	1.8	2.3	2.2	1.9	1.7	1.8	2.1	24
1984	2	2	2.5	2.4	2.4	2.3	2.5	2.4	2.2	2.1	2	2.1	26.9
1985	2.2	2.4	2.5	2.2	1.8	2.2	1.7	2.3	1.6	1.7	2	2.1	24.7
1986	1.5	2.1	2.1	2	1.7	2.1	2.1	1.7	1.2	1.5	1.6	1.6	21.2
1987	1.9	2.1	2.1	2	1.8	1.8	2.2	1.8	1.8	1.7	1.7	2.1	23
1988	2	2.2	2.2	2.3	2.2	2.3	2.4	1.6	1.1	1.4	1.5	1.7	22.9
1989	1.8	2.2	2.1	2	2.1	2.3	2.7	2.1	2	1.9	2.2	2.1	25.5
1990	1.9	1.8	1.6	0.9	0.5	2	0.7	0.8	0	0	0	0	10.2
1991	1.5	1.8	2.3	2	1.7	2	2.1	1.8	2	2.1	2.4	2.6	24.3
1992	2.1	2.2	2.4	2.3	2.2	1.7	2.3	1.7	1.6	1.6	2.1	2.1	24.3
1993	1.9	2.1	2	1.5	1.3	1.5	2	1.8	2	2.1	2.4	2.6	23.2
1994	3.4	3.7	2.5	2.3	1.8	1.8	2.3	1.9	2	2.1	2.4	2.6	28.8
1995	2.2	2.3	2.2	1.8	1.4	2.5	2.1	1.6	0.4	2.1	2.4	2.6	23.6
1996	2.6	2	2.1	2	1.6	1.8	2.1	1.7	1.2	1.3	1.5	1.6	21.5
1997	1.8	2	2.1	2	2.2	1.9	2	1.7	1.6	1.4	1.3	1.4	21.4
1998	1.6	1.7	2	2.2	2	2.5	2.2	1.6	1.1	1.3	1.4	1.5	21.1
1999	1.6	1.8	2.2	2.1	2.1	2.3	2	1.5	0	0	0	0	15.6
2000	1.6	1.8	2.2	1.8	1.7	2.2	2.2	2	1.5	0	0	0	17
2001	1.5	1.7	1.7	1.4	1.2	1.4	0.5	0.8	0.2	1.6	1.7	1.8	15.5
2002	1.8	1.8	1.9	1.8	1.4	2.3	2.1	1.8	0.9	1	1.3	1.5	19.6
2003	1.6	1.7	2	1.9	1.5	2	2	1.4	1	1.1	1.3	1.3	18.8
2004	1.7	1.9	2	2	1.8	2.1	2.2	1.5	1.5	1.2	1.3	1.6	20.8
2005	2	2.1	2.2	2	1.6	1.9	2	1.8	1.2	1.2	1.3	1.5	20.8
MWS	1.9	2.06	2.11	1.9	1.68	1.94	1.9	1.6	1.2	1.3	1.5	1.61	20.68

3.2 Patched wind speed (m/s) of Maichew station

year	Jan	Feb	Mar	Apr	May	Jun	Jul	Agu	Sep	Oct	Nov	Dec	MAWS
1976	1.2	1.1	1.3	1.4	1.6	1.7	2.9	2.5	1.6	1.2	1.2	1.2	18.9
1977	1	1.1	1.4	1.4	1.4	2.1	3.4	2.6	1.3	1.2	1.1	1.1	19.1
1978	1	1.2	1.4	1.2	1.3	1.9	3.4	2.2	1.2	1.2	1	1.1	18.1
1979	1.3	1.1	1.3	1.1	1.5	2.2	3	2.2	1.6	1.2	1	1	18.5
1980	1.1	1.4	1.2	1.1	1.2	2.2	3.6	2.2	1.1	0.9	1	1.1	18.1
1981	1.2	1.3	1.2	1.2	1.4	2.6	2.9	1.7	1.3	1.2	1.1	1.1	18.2
1982	1	1.3	1.4	1.1	1.2	3.7	3.3	2.4	1.4	1.1	1	1.1	20
1983	1.4	1.5	1.3	1.4	1.5	2.3	3	2.5	1.3	1.2	1.2	1.1	19.7
1984	1.1	1.5	1.5	1.9	2.1	1.8	3.6	2.7	1.4	1.3	1.2	1.2	21.3
1985	0.9	1.2	1.4	1.5	1.5	1.8	3.2	2.8	1.2	1.2	1	1.1	18.8
1986	1.1	1.2	1.3	1.4	1.5	2.3	3.8	2.7	1.4	1.2	1.1	1.2	20.2
1987	1.3	1.3	1.5	1.3	1.4	2	3.4	2.5	1.2	1.2	1.1	1.1	19.3
1988	1	1.3	1.4	1.6	1.5	2.4	3.7	2.5	1.3	1.2	1.3	1.2	20.4
1989	0.9	1.2	1.4	1.3	1.4	1.8	3.6	2.8	1.1	1.2	1.1	1.2	19
1990	1.3	1.2	1.3	1	0.9	2.4	3.7	2.5	1.1	0.9	0.7	0.9	17.9
1991	1	0.9	1.2	1.4	1.4	2.8	3.1	2.2	1.2	1.3	1.3	1.2	19
1992	1	1.2	1.4	1.5	1.7	2.3	3.7	2.8	1.6	1.2	1.1	1.1	20.6
1993	1.1	1.1	1.4	1.1	1.2	2.2	3.5	2.6	1.6	1.4	1.3	1.3	19.8
1994	1.4	1.2	1.6	1.5	1.5	3.3	3.8	2.5	1.4	1.3	1.2	1.1	21.8
1995	1.3	1.1	1.4	1.2	1.3	1.9	3	2.5	1.4	1.3	1.2	1.1	18.7
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	20.5
1997	1.1	1.3	1.3	1.3	1.5	1.9	3.1	2	1.3	1.2	1	1	18
1998	0.9	1	1.2	1.4	1.4	1.9	3.6	2.6	1.2	1.2	1.3	1.3	19
1999	1.2	1.4	1.4	1.5	1.6	2	3.3	2.2	1.1	0.9	1.1	1.1	18.8
2000	1.2	1.3	1.3	1.4	1.4	2.2	3.4	2.8	1.1	0.9	0.9	1	18.9
2001	1.2	1.3	1.3	1	1.2	2.4	3.2	2.5	1.2	1.2	1.1	1.1	18.7
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	17.9
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	19.1
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	18.8
2005	1.1	1.2	1.3	1.4	1.3	3	3	2.7	1.2	1.2	0.9	1	19.3
MWS	1.1	1.23	1.34	1.3	1.41	2.27	3.3	2.48	1.29	1.18	1.1	1.12	19.21

Appendix 4 Patched relative humidity

4.1.Patched relative humidity of Kobo station

year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	MARH
1959	63	59	64	63	65	51	48	59	54	45	36	41	648
1960	54	47	60	57	63	35	42	55	58	46	35	42	594
1961	44	57	66	64	44	35	39	60	67	60	47	54	637
1962	57	58	48	54	40	29	48	53	65	48	35	37	572
1963	47	58	59	56	38	30	46	52	70	49	36	38	579
1964	55	52	58	52	36	31	48	60	81	52	46	50	621
1965	66	67	39	60	43	26	50	57	43	45	40	42	578
1966	49	61	56	62	38	42	56	62	67	49	41	48	631
1967	59	53	51	45	34	25	48	55	61	69	48	56	604
1968	57	54	59	61	41	27	50	59	54	52	48	57	619
1969	64	45	66	63	53	29	52	60	55	51	55	74	667
1970	79	58	51	61	38	32	35	44	59	51	47	60	615
1971	67	64	46	56	40	27	51	62	64	56	48	65	646
1972	65	54	55	55	51	36	42	46	77	90	59	53	683
1973	62	60	30	29	37	24	43	55	51	47	41	41	520
1974	47	46	56	37	40	35	51	58	58	44	43	38	553
1975	47	63	47	58	41	43	50	59	60	45	38	46	597
1976	47	57	56	52	47	24	45	62	90	97	93	96	766
1977	87	52	50	43	47	22	54	56	72	60	60	54	657
1978	54	62	55	57	36	46	50	62	61	49	51	46	629
1979	63	56	46	50	33	32	51	49	63	51	41	46	581
1980	47	55	57	39	41	44	50	63	72	58	58	53	637
1981	59	52	37	28	36	41	47	64	46	46	54	53	563
1982	71	57	52	53	31	28	45	57	64	61	43	80	642
1983	71	66	33	42	41	27	44	59	62	55	36	56	592
1984	68	59	38	7	33	37	46	44	52	53	50	52	539
1985	74	57	55	57	49	36	30	46	57	49	37	64	611
1986	60	61	43	58	48	39	48	56	62	54	39	59	627
1987	51	44	66	55	58	32	31	52	37	44	30	34	534
1988	57	64	40	52	29	26	50	62	64	56	44	49	593
1989	58	60	55	62	32	25	37	52	49	45	42	60	577
1990	63	61	34	37	46	30	45	50	48	45	42	47	548
1991	52	51	59	60	37	21	54	72	58	50	49	91	654
1992	102	51	56	60	38	26	55	61	76	72	47	40	684
1993	48	64	64	64	68	37	35	48	48	44	36	34	590
1994	44	49	58	53	44	37	43	59	73	51	38	41	590
1995	47	60	56	63	69	30	42	54	77	50	38	60	646
1996	57	59	56	59	66	55	56	64	62	54	57	57	702
1997	70	48	55	58	38	43	40	49	56	55	56	63	631
1998	64	60	58	49	42	32	60	71	67	55	46	55	659
1999	67	66	45	42	38	25	41	62	63	50	42	41	582
2000	51	58	35	55	31	26	47	63	53	44	45	50	558
2001	57	72	44	49	42	44	35	47	56	55	40	44	585
2002	52	48	56	56	34	30	43	58	65	49	45	66	602
2003	51	40	54	61	25	28	54	67	58	46	42	75	601
2004	64	56	44	56	32	35	48	59	56	53	49	61	613
MMRH	59.52	56.5	51.5	52.4	42.46	32.9	46.2	57.04	61.11	53.26	45.5	53.67	612.11

4.2. Patched relative humidity of Maichew station

year	Jan	Feb	Mar	Apr	May	Jun	Jul	Agu	Sep	Oct	Nov	Dec	MARH
1959	56	79	71	63	64	52	62	64	64	59	55	51	740
1960	77	65	70	66	72	42	63	61	64	61	54	63	758
1961	73	80	73	55	48	40	65	66	57	60	64	78	759
1962	71	61	69	57	52	39	58	58	60	73	50	63	711
1963	68	67	65	74	56	40	68	70	68	69	54	75	774
1964	71	72	66	52	45	39	58	58	65	64	61	51	702
1965	52	42	52	67	51	32	53	52	60	59	61	71	652
1966	58	73	65	53	46	47	67	69	61	69	66	58	732
1967	54	62	66	62	50	34	56	59	53	67	65	76	704
1968	62	69	67	53	46	35	57	63	58	59	58	57	684
1969	64	72	67	55	66	34	58	61	60	55	69	48	709
1970	53	62	59	46	42	41	62	59	59	63	59	63	668
1971	58	49	58	51	54	35	59	65	60	60	60	65	674
1972	49	63	59	70	59	45	66	72	66	78	68	72	767
1973	49	49	43	49	52	35	61	64	63	63	58	57	643
1974	62	72	69	49	53	40	65	72	63	65	53	50	713
1975	74	94	72	63	60	47	63	61	63	68	67	71	803
1976	47	62	64	53	56	32	66	64	66	54	70	59	693
1977	68	63	63	51	47	31	58	62	62	52	59	60	676
1978	62	64	68	55	44	51	67	64	63	63	65	78	744
1979	63	59	64	56	46	38	55	73	65	66	57	66	708
1980	57	70	65	47	41	49	61	69	63	65	59	51	697
1981	41	41	53	56	44	49	63	62	63	49	54	44	619
1982	54	58	59	53	40	34	55	65	62	62	56	64	662
1983	48	48	54	58	53	32	57	70	63	59	50	53	645
1984	40	31	45	42	49	41	62	64	61	54	55	51	595
1985	42	38	58	51	52	44	67	57	61	67	57	48	642
1986	32	47	48	56	52	43	59	57	54	65	68	76	657
1987	81	68	72	62	57	38	58	59	62	50	46	69	722
1988	91	71	66	46	44	34	66	58	57	62	58	68	721
1989	71	64	67	47	39	33	57	68	65	62	54	56	683
1990	28	45	54	50	46	36	54	62	62	69	60	68	634
1991	66	83	70	70	51	28	55	57	61	54	68	62	725
1992	71	80	64	47	49	34	53	65	62	66	68	85	744
1993	81	81	73	79	70	48	63	59	59	64	60	57	794
1994	56	78	71	59	56	48	69	73	62	56	65	60	753
1995	54	67	67	73	72	37	65	71	63	55	55	69	748
1996	75	57	70	66	65	51	61	64	55	54	60	58	736
1997	68	52	66	60	51	51	63	58	54	68	77	66	734
1998	80	72	68	54	62	39	63	71	66	63	52	44	734
1999	59	37	56	44	38	32	66	67	66	72	55	61	653
2000	51	39	44	45	43	36	64	71	64	74	70	69	670
2001	68	53	68	55	52	50	67	73	67	64	60	57	734
2002	76	56	63	56	41	39	51	62	64	57	55	76	696
2003	67	72	58	47	40	38	61	68	64	60	56	70	701
2004	65	56	50	69	34	42	56	66	58	60	60	66	682
MMRH	61.15	61.8	62.6	56.4	51.1	39.9	60.9	64.2	61.7	62.13	59.8	62.61	704.23

4.3 Patched relative humidity of Mehoni station

year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	MARH
1959	48	53	54	50	50	51	61	53	49	48	56	53	626
1960	58	55	53	51	48	44	60	56	58	57	53	49	642
1961	42	51	54	48	59	58	80	56	49	57	52	54	660
1962	46	52	53	53	52	62	52	61	75	60	54	51	671
1963	48	51	53	51	49	51	81	78	75	64	52	52	705
1964	51	53	54	54	56	69	53	61	62	54	58	55	680
1965	54	51	54	50	52	80	47	55	51	48	52	51	645
1966	49	52	54	50	55	52	86	63	70	57	57	54	699
1967	50	59	51	55	59	79	54	60	65	58	53	54	697
1968	59	52	55	49	49	67	60	57	54	52	58	55	667
1969	60	58	54	47	42	69	65	56	49	40	58	57	655
1970	50	54	55	50	61	57	52	62	60	57	56	56	670
1971	52	54	54	55	49	70	78	61	61	53	56	55	698
1972	62	57	53	52	50	48	84	127	93	67	53	54	800
1973	57	53	54	58	61	68	68	57	64	62	55	52	709
1974	44	52	54	59	55	55	93	76	74	59	58	50	729
1975	33	51	53	49	42	37	51	54	63	55	48	50	586
1976	44	52	55	52	43	58	73	58	45	43	57	57	637
1977	54	62	51	56	58	75	87	60	56	52	53	54	718
1978	49	53	53	53	47	59	86	54	55	53	55	53	670
1979	65	53	55	56	56	58	53	85	79	62	56	54	732
1980	55	52	54	59	60	61	66	64	58	60	60	57	706
1981	57	57	53	59	59	59	83	53	47	50	61	56	694
1982	56	55	54	54	61	61	53	71	66	59	54	56	700
1983	63	58	51	55	59	66	96	65	58	56	59	56	742
1984	64	60	51	66	60	62	89	74	55	52	59	55	747
1985	62	56	54	54	49	33	59	58	58	55	59	56	653
1986	65	69	53	51	60	62	56	55	62	52	52	53	690
1987	45	53	55	52	60	73	59	63	46	48	50	44	648
1988	45	50	55	53	48	43	57	53	59	52	55	53	623
1989	55	52	55	49	57	74	63	80	67	59	59	56	726
1990	69	63	54	57	62	62	48	78	74	64	53	53	737
1991	51	54	55	49	58	66	69	49	43	46	59	56	655
1992	59	52	55	49	46	74	48	57	69	55	47	50	661
1993	46	50	54	45	44	54	63	63	57	58	49	48	631
1994	52	53	52	53	51	43	79	66	71	53	55	49	677
1995	54	53	55	48	43	57	51	74	89	59	53	54	690
1996	53	52	55	51	51	56	79	59	58	47	57	56	674
1997	61	58	51	52	43	31	57	63	74	59	54	55	658
1998	49	56	54	55	52	49	72	53	44	41	56	55	636
1999	58	56	52	57	59	76	79	64	65	58	54	51	729
2000	60	56	52	52	51	69	84	63	58	63	54	54	716
2001	52	57	54	57	50	35	66	97	65	57	50	52	692
2002	51	54	51	53	66	61	52	53	40	42	58	55	636
2003	49	56	53	49	39	55	75	54	61	54	57	56	658
2004	55	56	52	53	56	53	68	57	53	50	59	56	668
MMRH	53.5	54.7	53.5	52.8	52.98	58.7	67.3	63.83	60.96	54.5	55.07	53.52	681

Appendix 5 Patched rainfall data

5.1 Patched rainfall data Alamata station

year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	annual
1954	0	48	17	1	45	9	1	98	46	1	1	9	495
1955	1	1	11	3	14	0	1	44	90	8	1	18	1161
1956	9	26	50	3	1	3	2	22	30	2	6	19	1282
1957	1	50	25	6	54	0	2	25	57	2	0	4	961
1958	1	35	4	1	9	9	7	55	30	0	5	49	508
1959	4	22	81	9	27	1	5	30	81	4	1	61	808
1960	1	1	18	4	52	1	1	93	25	1	1	7	543
1961	2	51	22	5	51	2	3	17	67	1	0	3	428
1962	2	2	17	1	33	2	6	15	24	1	8	31	746
1963	3	63	40	3	41	5	8	43	30	1	1	17	1001
1964	1	0	15	8	54	0	2	19	61	3	0	0	728
1965	2	68	30	1	97	6	2	39	95	8	2	27	1055
1966	1	0	18	1	30	1	9	0	10	0	1	26	471
1967	4	2	98	6	16	4	4	27	35	0	1	0	553
1968	2	0	18	6	18	1	3	18	30	4	0	37	565
1969	1	24	93	7	40	0	1	96	22	0	0	0	559
1970	6	43	15	4	9	4	9	12	42	1	0	0	399
1971	1	2	67	3	11	3	3	27	53	3	0	1	858
1972	6	1	14	1	11	3	2	15	26	8	4	5	662
1973	6	1	10	1	12	3	4	71	31	1	4	1	498
1974	5	12	31	2	85	1	1	7	22	0	1	67	427
1975	9	3	96	1	53	1	4	34	75	3	0	36	742
1976	1	12	53	1	11	0	1	18	68	3	5	7	849
1977	3	18	10	7	12	1	1	23	55	1	2	12	934
1978	2	18	29	2	10	1	9	0	10	9	5	10	463
1979	1	6	84	8	67	0	0	17	48	4	0	32	655
1980	1	16	33	6	4	1	3	63	29	6	0	2	822
1981	4	64	43	8	13	3	9	13	49	4	0	11	534
1982	3	93	14	6	70	0	3	17	48	1	2	6	685
1983	3	93	14	6	13	1	9	20	36	7	5	0	700
1984	0	6	0	8	11	0	2	6	21	0	6	77	263
1985	1	0	17	1	90	1	5	13	28	5	0	13	497
1986	0	66	38	1	31	3	1	23	54	0	0	12	866
1987	0	27	22	7	12	1	4	13	52	0	0	22	670
1988	2	13	50	1	0	0	2	24	77	3	0	5	920
1989	2	46	13	1	19	0	8	65	36	9	0	6	553
1990	3	88	26	8	29	5	2	53	27	0	1	0	1165
1991	4	15	59	4	28	0	1	45	89	1	0	10	1188
1992	1	43	16	2	78	0	7	24	79	4	9	13	740
1993	4	99	65	1	97	6	9	53	11	3	0	6	800
1994	0	0	11	5	14	0	1	28	77	0	2	1	715
1995	0	69	14	2	93	1	1	20	52	1	0	97	1016
1996	1	0	69	1	11	2	7	28	36	8	5	0	924
1997	4	0	12	2	29	2	8	54	72	1	1	0	793
1998	1	23	26	3	20	0	3	27	64	1	0	0	985
1999	4	0	21	9	7	1	2	43	67	5	0	0	847
2000	0	0	10	4	74	6	2	44	68	1	8	73	1068
2001	0	0	15	9	30	1	2	24	25	1	1	3	731
2002	7	0	18	1	8	4	7	21	46	1	0	90	651
2003	7	70	42	9	25	1	1	23	23	0	0	10	700

2004	3	16	40	1	14	5	1	24	41	8	2	20	769
MMR	2.549	26.59	32.43	3.941	33	2.059	3.75	32	46.47	2.73	1.784	18.75	744.176

5.2. Patched rainfall of Kobo station

year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	annual
1953	6	1	52	21	5	0	202	175	60	11	0	0	533
1954	0	107	14	43	57	0	75	40	15	117	1	1	470
1955	1	1	42	11	87	18	394	325	84	50	172	77	1262
1956	17	16	56	95	5	3	98	70	108	95	303	21	887
1957	22	55	0	85	73	36	199	256	57	37	0	0	820
1958	0	133	13	95	16	0	30	98	43	0	16	96	540
1959	14	16	30	95	58	15	205	263	64	80	0	9	849
1960	9	0	83	43	30	22	195	173	5	38	3	1	602
1961	2	19	14	1	29	4	249	225	84	88	0	1	716
1962	2	3	116	89	44	9	21	152	70	33	4	26	566
1963	25	12	16	95	62	0	63	114	34	10	2	13	446
1964	54	0	74	91	45	14	149	227	109	153	0	0	916
1965	13	31	42	8	41	1	216	314	45	227	2	4	944
1966	0	0	29	76	52	16	52	39	107	0	1	11	383
1967	3	1	32	54	23	27	40	221	82	2	9	2	496
1968	24	0	83	87	10	2	1	87	81	5	0	4	384
1969	15	7	9	55	71	25	29	80	75	3	0	0	369
1970	6	21	31	88	20	13	49	152	54	4	0	0	438
1971	13	2	47	17	8	1	184	177	35	37	0	0	521
1972	24	0	52	95	102	1	65	141	89	78	19	7	673
1973	2	1	52	90	36	4	26	116	68	32	3	4	434
1974	9	6	106	17	94	8	43	63	73	8	38	13	478
1975	67	0	30	40	28	21	92	263	126	32	0	3	702
1976	0	13	17	127	116	1	93	143	37	13	29	27	616
1977	17	4	88	57	124	6	156	237	67	111	7	4	878
1978	2	19	41	42	36	5	236	76	28	17	12	18	532
1979	89	2	29	11	78	17	149	181	111	46	0	15	728
1980	1	106	24	54	26	28	199	220	47	33	0	0	738
1981	0	16	21	88	10	0	256	278	66	46	0	4	785
1982	17	20	39	80	28	38	44	175	125	119	4	7	696
1983	5	19	67	88	115	25	26	74	27	24	2	0	472
1984	0	10	3	16	148	4	8	14	29	0	6	29	267
1985	4	0	60	77	44	6	59	133	101	9	0	0	493
1986	0	34	10	73	91	75	134	226	90	0	0	27	760
1987	0	1	95	51	128	7	16	116	37	65	0	13	529
1988	38	58	5	45	0	13	193	166	100	22	0	0	640
1989	17	24	71	71	19	0	69	126	39	21	0	0	457
1990	16	163	58	75	94	11	25	31	63	54	0	0	590
1991	8	48	13	95	103	4	313	315	22	115	0	1	1037
1992	95	14	78	33	130	1	4	22	4	152	21	12	566
1993	65	7	8	88	45	32	84	143	23	94	0	0	589
1994	1	0	14	59	18	5	181	199	17	69	5	0	568
1995	0	185	72	86	37	21	223	220	46	55	0	6	951
1996	79	0	31	75	133	53	147	205	67	18	64	2	874
1997	6	0	43	58	48	52	111	94	37	196	49	0	694
1998	54	33	24	39	12	4	326	312	51	6	0	0	861
1999	20	0	34	48	12	2	231	316	107	25	0	0	795
2000	1	0	2	76	42	5	227	332	48	88	24	83	928
2001	0	0	71	19	16	2	231	220	98	8	4	2	671
2002	5	0	0	0	13	3	100	296	117	16	0	67	617

2003	41	33	35	66	31	11	140	258	54	0	0	43	712
2004	30	1	28	88	3	26	116	162	9	54	36	10	563
MMR	18.66	22.68	40.76	62.24	52.7	13.94	130	177	63.2	49.8	16.7	13.24	654.538

5.3. Patched rainfall data of Maichew station

year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	annual
1953	2	65	3	60	64	7	252	242	89	8	5	63	860
1954	0	37	57	9	71	20	283	336	136	37	0	14	1000
1955	28	4	52	96	46	4	174	145	89	2	10	22	672
1956	7	1	35	153	0	12	169	222	122	44	1	0	766
1957	0	19	195	118	51	7	77	369	41	28	5	0	910
1958	17	23	19	117	12	25	208	161	16	13	1	7	619
1959	0	38	48	10	52	10	335	232	96	57	16	3	897
1960	11	10	58	52	119	2	63	210	63	11	0	18	617
1961	0	97	22	143	8	18	219	178	32	43	2	0	762
1962	544	0	67	49	80	1	111	159	115	1	1	11	1139
1963	1	2	36	128	116	26	106	23	31	15	208	16	708
1964	0	55	46	59	37	36	337	171	92	53	39	55	980
1965	0	34	58	122	5	2	60	233	109	98	42	15	778
1966	7	67	42	135	19	27	146	263	33	60	0	1	800
1967	347	2	154	56	12	5	264	322	45	4	0	0	1211
1968	3	7	7	62	15	29	256	216	45	128	2	32	802
1969	0	138	34	82	38	36	60	146	36	71	10	0	651
1970	12	0	5	0	101	0	43	84	142	69	9	69	534
1971	3	1	86	16	97	34	95	72	29	25	33	5	496
1972	0	0	0	31	43	9	233	139	77	23	7	51	613
1973	3	47	1	135	121	80	128	279	95	16	1	1	907
1974	30	50	6	55	29	77	168	229	22	0	89	3	758
1975	1	29	83	118	41	8	147	300	59	66	42	5	899
1976	20	14	84	10	58	52	21	312	71	184	0	31	857
1977	6	10	132	59	60	47	272	233	46	65	42	31	1003
1978	55	5	49	36	190	96	126	197	154	115	0	0	1023
1979	7	174	60	69	17	66	120	226	100	104	0	0	943
1980	0	0	124	72	77	3	136	161	35	25	0	0	633
1981	50	86	79	120	32	0	32	82	44	74	7	0	606
1982	2	4	106	91	78	9	103	196	39	14	43	0	685
1983	0	1	34	34	231	70	52	81	118	0	0	26	647
1984	49	0	0	164	135	36	108	103	71	56	0	13	735
1985	0	34	3	76	71	92	112	202	120	4	120	20	854
1986	0	58	205	106	206	12	9	21	28	42	0	0	687
1987	0	55	6	36	12	9	226	273	32	14	57	3	723
1988	0	2	94	182	67	0	308	153	17	80	43	12	958
1989	3	4	3	76	110	9	47	135	67	3	45	0	502
1990	4	18	19	50	169	127	69	75	45	30	3	6	615
1991	27	3	56	20	103	1	144	251	50	53	49	66	823
1992	41	35	76	135	126	3	58	126	34	43	0	1	678
1993	0	19	53	84	42	29	234	311	69	5	20	4	870
1994	0	60	27	123	73	21	252	196	54	16	0	61	883
1995	9	1	124	146	141	67	117	247	42	4	57	0	955
1996	16	0	52	59	38	84	167	64	64	206	81	0	831
1997	65	33	35	39	117	4	332	215	224	11	0	0	1075
1998	45	0	11	22	16	13	177	254	78	110	0	2	728
1999	0	0	6	18	65	12	196	194	127	151	62	75	906
2000	0	2	93	9	35	27	212	283	84	25	0	11	781

2001	84	0	34	68	41	22	67	189	93	19	0	34	651
2002	24	38	93	194	13	14	107	321	32	5	0	18	859
2003	13	5	20	127	1	59	141	247	27	38	3	0	681
2004	0	9	6	48	14	2	78	239	95	92	1	0	584
MMR	30.68	25.88	54.76	80.2	67.6	28.68	148	195	68.98	48.3	23.02	14.56	785.9

5.4 Patched rainfall data of Mehoni station

year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	annual
1953	47	0	89	13	2	36	0	81	2	11	0	0	281
1954	0	20	75	2	2	140	0	36	0	1	1	0	277
1955	5	0	54	4	75	0	1	250	12	0	156	10	567
1956	0	4	38	340	5	2	199	18	12	0	633	45	1296
1957	15	8	54	44	87	0	10	155	8	4	0	0	385
1958	7	19	54	243	0	10	31	78	171	0	31	3	647
1959	4	5	57	133	49	3	15	162	2	35	0	0	465
1960	31	0	151	13	52	14	2	44	2	0	0	0	309
1961	24	7	54	0	31	0	131	203	119	11	0	0	580
1962	3	0	215	209	34	1	47	49	18	0	40	70	686
1963	7	20	26	341	2	38	109	53	315	0	4	17	932
1964	11	0	42	95	39	66	18	220	1	12	0	1	505
1965	2	7	77	0	14	0	5	258	1	80	0	1	445
1966	6	0	29	107	51	7	85	5	79	0	0	0	369
1967	1	0	144	29	41	872	31	94	181	0	9	10	1412
1968	0	0	18	33	5	10	45	52	122	2	0	1	288
1969	23	2	111	58	65	1	17	25	118	0	0	0	420
1970	6	6	332	8	41	20	50	116	0	2	0	0	581
1971	0	0	550	9	3	228	0	128	1	4	0	0	923
1972	0	0	26	170	12	23	192	64	4	1	8	8	508
1973	127	0	11	152	22	12	62	32	18	11	1	2	450
1974	3	2	219	4	38	22	221	8	1265	0	20	81	1883
1975	61	0	17	0	21	23	112	194	101	8	0	12	549
1976	0	2	116	95	140	0	45	84	25	58	45	2	612
1977	53	1	136	45	51	11	49	100	5	128	0	0	579
1978	0	24	106	9	21	0	76	22	0	0	32	82	372
1979	54	0	80	57	72	0	15	142	0	50	0	4	474
1980	0	84	47	84	46	30	82	128	33	0	0	0	534
1981	9	16	60	96	3	29	180	145	13	4	0	0	555
1982	0	6	10	30	99	1	2	129	7	4	7	35	330
1983	0	24	31	61	40	1	0	76	0	1	1	1	236
1984	10	1	92	0	14	0	0	22	2	0	1	2	144
1985	2	0	32	153	0	2	11	177	0	0	0	1	378
1986	5	7	264	187	69	64	1	63	10	0	0	7	677
1987	6	1	23	32	81	2	0	46	0	0	0	2	193
1988	14	30	8	130	2	16	321	108	172	34	0	0	1835
1989	0	11	45	105	53	0	3	46	11	7	0	0	281
1990	28	769	127	42	49	20	3	38	67	3	1	0	1147
1991	19	18	111	85	68	1	4	264	3	6	0	3	582
1992	2	3	83	8	52	27	3	6	6	65	92	10	357
1993	0	8	14	251	54	83	9	88	2	1	0	0	510
1994	0	0	25	49	28	0	11	116	25	3	3	6	266
1995	0	39	59	217	61	14	71	58	39	0	0	0	558
1996	13	0	8	152	45	12	0	90	27	1	87	0	435
1997	162	0	44	9	28	64	189	99	0	66	56	0	717
1998	1	17	20	15	33	1	7	229	25	0	0	6	354

1999	32	0	107	3	36	1	36	237	22	22	0	0	496
2000	0	0	29	32	30	16	271	283	4	0	176	23	864
2001	30	0	27	1	4	65	152	126	27	0	25	1	458
2002	1	0	16	41	8	1	12	150	14	0	0	2	245
2003	48	36	35	51	15	0	22	150	100	0	0	0	457
2004	18	1	91	188	0	33	0	139	92	95	3	5	665
MMR	16.86	23.56	82.5	84.4	37.8	36.92	59.2	111	65.62	14.4	28.62	9.06	590.22

5.5.Patched rainfall data of Waja station

year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	annual
1953	0	3	108	114	18	14	143	200	22	12	3	0	637
1954	13	121	28	32	1	1	234	140	27	0	0	0	597
1955	10	19	125	149	9	0	210	252	92	6	5	28	905
1956	8	19	27	128	104	135	9	324	10	43	32	60	899
1957	0	2	30	136	16	0	166	173	58	2	0	0	583
1958	5	2	25	51	111	315	25	141	19	14	5	33	746
1959	1	4	22	102	9	8	153	128	86	8	1	8	530
1960	1	1	75	110	3	0	193	49	23	0	2	1	458
1961	0	0	19	28	2	2	23	111	133	46	0	0	364
1962	12	22	94	146	164	15	40	219	11	29	6	53	811
1963	1	9	9	132	699	121	105	207	12	61	8	83	1447
1964	2	2	91	20	13	10	50	297	192	15	0	2	694
1965	35	1	38	69	3	4	201	125	181	17	0	4	678
1966	0	5	92	41	56	7	58	279	13	1	28	1	581
1967	30	12	36	72	8	12	88	194	33	4	140	4	633
1968	202	9	92	73	20	25	44	319	5	6	2	1	798
1969	2	0	57	7	16	2	103	311	30	1	3	0	532
1970	1	0	89	145	2	22	56	79	12	5	0	0	411
1971	371	687	122	128	1	3	234	87	92	0	0	0	1725
1972	341	102	122	147	35	2	7	123	48	414	9	1	1351
1973	0	2	36	33	89	8	70	169	7	4	1	7	426
1974	5	0	42	2	2	10	18	367	4	33	216	30	729
1975	0	4	31	145	16	7	23	260	31	47	0	7	571
1976	21	299	28	82	19	1	85	241	131	0	28	5	940
1977	0	30	21	135	108	6	34	292	82	157	0	0	865
1978	17	7	21	1	2	4	50	68	10	3	206	97	486
1979	1	0	101	7	1	0	180	124	77	0	1	8	500
1980	10	5	11	141	275	17	48	113	65	3	1	0	689
1981	0	0	1	132	29	47	183	176	35	3	1	0	607
1982	27	430	7	108	5	17	74	104	63	14	0	3	852
1983	54	30	37	23	164	10	13	53	42	0	18	1	445
1984	0	0	17	26	146	4	35	70	0	0	0	0	298
1985	3	0	32	128	69	45	101	85	80	60	0	8	611
1986	0	79	13	93	38	36	132	182	110	0	0	67	750
1987	0	66	260	20	114	0	18	125	453	8	0	18	1082
1988	2	0	18	56	2	12	260	127	79	19	0	0	575
1989	23	21	106	108	7	0	64	130	15	4	0	1	479
1990	0	0	23	29	158	2	118	200	86	2	18	0	636
1991	0	78	91	174	37	0	152	197	38	11	0	98	876
1992	20	0	83	142	166	26	96	194	55	13	48	5	848
1993	10	0	93	48	0	6	68	54	13	223	120	0	635
1994	76	41	37	32	34	4	308	380	55	8	0	0	975
1995	41	30	42	36	4	3	240	196	43	85	0	0	720
1996	5	0	0	56	19	7	161	252	7	37	31	0	575

1997	0	0	58	20	27	339	139	197	37	10	0	0	827
1998	63	0	22	64	0	0	84	139	55	0	0	88	515
1999	0	61	42	88	0	40	92	324	47	0	1	43	738
2000	74	1	34	0	6	23	0	113	25	4	43	8	331
2001	0	8	17	133	91	7	142	175	92	0	61	0	726
2002	8	1	31	27	9	19	91	160	86	2	1	5	440
2003	2	0	32	44	14	41	151	308	3	22	1	8	626
2004	0	0	87	97	91	51	35	193	13	9	0	14	590
MMR	29.68	41.78	52.78	78.28	60.3	29.5	101	184	59.78	29.1	20.74	16	702.18

5.6. Patched rainfall data of Korem station

year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	annual
1953	14	10	180	33	18	42	36	176	62	39	0	1	611
1954	0	13	60	20	64	87	2	44	51	32	7	7	387
1955	12	16	148	59	207	46	60	331	83	1	38	25	1026
1956	84	338	9	120	34	0	309	341	91	15	103	52	1496
1957	462	38	94	82	152	11	124	207	63	85	0	17	1335
1958	0	9	34	69	13	0	210	100	93	0	146	96	770
1959	68	10	44	57	51	11	161	201	104	194	3	37	941
1960	17	16	84	91	113	75	62	32	27	21	2	18	558
1961	2	5	144	22	73	6	288	299	100	150	0	3	1092
1962	0	24	101	147	48	1	222	327	35	12	169	26	1112
1963	485	141	19	158	23	3	276	276	85	7	16	41	1530
1964	201	2	85	57	47	30	141	304	50	135	2	0	1054
1965	16	16	123	76	118	20	79	47	83	106	6	16	706
1966	15	0	63	107	65	33	230	179	83	3	0	89	867
1967	1	17	105	60	36	33	195	454	96	2	40	2	1041
1968	16	0	80	83	34	0	216	258	106	69	1	56	919
1969	148	8	198	57	113	1	137	218	101	5	1	4	991
1970	17	19	135	53	22	6	217	135	55	50	0	0	709
1971	2	3	136	44	30	95	43	14	44	69	0	7	487
1972	9	6	42	125	215	15	311	193	78	27	25	4	1050
1973	155	27	49	121	51	8	232	221	83	127	5	19	1098
1974	42	335	144	46	63	2	317	481	102	15	339	15	2041
1975	78	2	67	85	89	33	268	371	109	45	0	47	1194
1976	1	23	93	61	206	9	207	135	88	256	40	77	1196
1977	29	9	80	121	159	18	226	310	52	369	9	29	1411
1978	6	19	182	48	22	13	240	71	30	8	78	30	747
1979	102	3	135	48	238	36	132	216	89	113	0	18	1130
1980	12	149	48	127	21	19	277	255	87	51	7	0	1053
1981	1	30	155	123	55	2	290	286	94	55	0	6	1097
1982	108	71	101	125	155	5	54	214	62	65	168	33	1161
1983	26	0	18	66	61	0	0	41	5	65	7	0	289
1984	0	46	67	42	235	0	16	10	23	0	18	18	475
1985	9	2	80	180	44	14	109	82	27	2	0	36	585
1986	1	66	131	114	335	62	47	392	82	0	0	17	1404
1987	0	1	147	67	241	12	31	321	37	57	0	29	943
1988	7	127	8	85	20	12	453	374	143	144	0	20	1393
1989	71	73	89	83	75	71	87	111	89	70	0	82	901
1990	80	81	82	82	79	52	83	82	83	80	3	0	787
1991	79	80	81	80	81	80	83	83	82	80	0	80	889
1992	81	80	80	82	80	79	83	85	82	81	80	80	973
1993	55	35	47	84	83	6	106	100	85	31	0	12	644
1994	0	0	80	80	81	80	88	86	82	79	81	0	737
1995	0	119	35	95	80	41	224	420	55	13	0	80	1162

1996	46	264	21	83	141	12	18	152	56	17	60	6	876
1997	34	35	178	72	83	5	296	84	7	93	127	5	1019
1998	138	131	32	67	126	73	128	218	102	29	3	12	1059
1999	174	0	24	41	57	1	206	481	102	93	0	9	1188
2000	2	8	35	42	122	6	316	507	87	11	25	49	1210
2001	2	3	130	22	36	51	283	380	62	13	9	13	1004
2002	65	1	34	107	16	3	137	229	90	8	0	93	783
2003	24	24	100	75	23	20	168	381	78	2	4	30	929
2004	114	0	150	110	24	19	11	111	84	194	51	73	941
MMR	61.94	50.24	86.94	82.62	91.5	24.6	170	224	74.32	64.3	33.32	30.22	1000.06

5.7. Patched rainfall data of Chercher station

year	Jan	Feb	Mar	Apr	May	Jun	Jul	Agu	Sep	Oct	Nov	Dec	annual
1953	3	1	59	41	13	19	164	75	32	2	0	0	409
1954	0	0	25	110	61	199	132	21	22	185	1	0	756
1955	1	114	2	51	111	149	120	160	73	21	137	1	940
1956	17	353	0	2	12	0	142	460	140	25	303	2	1456
1957	9	44	0	32	82	21	82	133	43	63	0	1	510
1958	0	0	25	14	10	0	128	92	41	0	24	5	339
1959	16	7	7	40	50	35	146	103	47	24	1	6	482
1960	15	5	36	60	60	41	118	30	22	31	3	2	423
1961	3	0	76	59	79	0	176	231	80	77	0	1	782
1962	3	160	0	11	41	0	132	237	46	15	10	3	658
1963	76	45	1	6	18	8	127	230	56	1	3	9	580
1964	40	1	59	38	57	1	143	186	88	188	0	0	801
1965	24	1	73	54	70	40	105	56	23	430	2	5	883
1966	1	1	31	21	36	2	110	167	48	0	1	5	423
1967	2	43	23	56	14	6	165	327	105	0	11	1	753
1968	22	10	15	25	32	0	190	257	67	1	0	34	653
1969	15	0	93	48	62	2	115	166	50	0	0	1	552
1970	4	458	0	58	22	1	91	93	40	1	0	0	768
1971	10	309	1	71	34	362	77	35	28	46	0	1	974
1972	23	379	0	33	92	0	161	180	37	35	34	1	975
1973	3	0	18	17	50	1	119	182	52	21	7	0	470
1974	3	0	66	54	76	0	160	474	172	0	37	28	1070
1975	159	58	24	71	44	40	187	269	130	2	0	16	1000
1976	0	9	46	80	81	5	98	124	31	37	37	4	552
1977	28	3	69	31	77	32	126	308	62	168	10	11	925
1978	4	21	37	40	48	2	139	59	26	0	13	9	398
1979	83	0	64	16	102	11	120	215	53	52	0	3	719
1980	3	109	0	12	12	29	79	114	93	77	0	0	528
1981	0	0	184	24	30	0	123	162	41	36	0	0	600
1982	16	23	15	64	85	0	146	96	47	66	9	0	567
1983	2	48	0	39	34	0	112	53	20	7	3	0	318
1984	0	24	5	93	86	0	125	35	32	0	7	1	408
1985	7	0	56	9	54	12	129	65	44	7	0	12	395
1986	2	5	70	18	64	25	78	312	114	0	0	76	764
1987	1	8	0	85	81	113	111	194	73	14	0	15	695
1988	77	53	3	27	15	1	135	200	146	23	0	1	681
1989	24	48	2	9	66	332	105	90	40	8	0	3	727
1990	16	20	3	24	34	6	121	136	88	3	1	0	452
1991	6	30	8	21	61	487	97	50	36	241	0	21	1058
1992	240	4	20	37	51	30	95	66	28	98	22	11	702
1993	101	1	55	12	90	0	130	59	37	135	0	1	621
1994	0	1	65	13	42	12	124	51	29	8	8	0	353

1995	0	32	4	10	80	20	97	268	53	25	1	10	600
1996	143	14	48	25	93	370	91	116	46	7	67	0	1020
1997	6	0	101	41	38	5	112	50	24	198	78	0	653
1998	21	55	4	37	62	265	91	207	53	3	0	1	799
1999	22	180	0	63	42	1	105	511	74	13	0	1	1012
2000	1	10	7	26	96	0	116	370	99	81	36	2	844
2001	0	67	40	99	26	2	114	315	112	4	8	1	788
2002	11	1	14	34	20	0	114	98	63	25	0	8	388
2003	45	7	21	29	46	100	128	199	42	0	0	2	619
2004	50	1	44	13	28	60	100	95	24	18	17	2	452
MMR	27.1	55.24	30.7	37.04	53.9	52.58	121	174	60.36	46.7	17.8	6.34	682.6

Appendix 6 runoff of Golina River,MCM

YEAR	Jan.	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	TOTAL
1976	1.06	0.93	4.58	3.62	1.49	3.01	4.76	7.27	4.40	0.95	0.95	0.93	33.96
1977	2.77	1.26	2.77	2.01	7.37	2.10	4.79	13.93	4.82	4.53	3.80	4.00	54.15
1978	1.46	1.48	1.46	4.46	11.18	4.32	13.44	20.21	0.81	0.69	2.36	2.57	64.45
1984	10.18	8.59	8.08	9.99	9.04	4.34	5.64	5.54	5.93	4.17	4.06	5.54	81.10
1985	5.36	6.24	8.17	10.07	1.09	1.13	2.02	2.78	3.52	0.62	0.29	0.85	42.15
1986	0.40	2.78	1.36	1.49	0.29	0.36	1.94	6.58	9.08	10.82	7.41	7.69	50.20
1987	7.37	6.06	7.32	8.63	10.08	15.10	15.70	19.86	17.05	3.41	2.91	3.16	116.65
1989	2.44	2.15	3.48	4.72	2.22	1.99	2.79	6.39	3.74	2.18	1.97	2.30	36.36
1990	5.38	11.37	9.27	8.07	7.17	5.14	6.63	6.28	7.33	5.68	4.85	4.56	81.73
1991	4.82	4.80	8.16	5.87	6.72	5.18	7.82	3.43	3.03	1.19	1.03	1.15	53.19
1992	6.00	7.37	8.75	5.27	4.84	4.24	4.71	9.49	5.73	3.39	2.91	3.16	65.86
Mean	4.30	4.82	5.76	5.84	5.59	4.26	6.39	9.25	5.95	3.42	2.96	3.26	61.80

Appendix 7 chloride content in rainfall and groundwater

SAMPLE ID	X	Y	Z	Cl(mg/l)	1/Cl(mg/l)	Remark
Waja Rainfall				4.46		PD,AAU laboratory
Alamata Rainfall				1.57		,,
Korem Rainfall				0.68		,,
Gerjale Rainfall				0.68		,,
ACCR				**1.8475**		
Waregeba BH	572733	1412322	1708	22.58	0.0443	,,
Fachagama BH	579095	1402231	1556	15.71	0.0634	,,
Dualga BH	569552	1409316	1745	27.4	0.0365	,,
Sum					**0.1442**	
HM of GWC					**20.8**	
Kobo Rainfall				7.7		PD, Jije analytical service laboratory
Hormate Rainfall				6.1		,,
Amido Rainfall				9.7		,,
Robit Rainfall				8.6		,,
ACCR				**8.025**		
HG10	570348	1339366	1451	17	0.0588	SD
HG11	571055	1335915	1434	21.12	0.0473	SD
HG12	572295	1335804	1418	20.2	0.0495	SD
HG14	571067	1336466	1433	21.12	0.0473	SD
HG15	574997	1330600	1422	19.85	0.0504	SD
WG12	573140	1357524	1395	20.79	0.0481	SD
WG13	573250	1357002	1396	22.08	0.0453	SD
Sum					**0.3467**	
HM of GWC					**20.19**	

ACCR= average chloride concentration in rainfall, HM= harmonic mean, GWC = groundwater chloride, PD = primary data, SD= secondary data.

Appendix 8. Proposed Growing Period and Cropping Calendar (MOWR,2008)

Crop season	Crop Type	Growing periods in days	Area Cover %	Land preparation	Sowing/Planting		Field management	Harvesting
					Wet season	Dry season		
Wet season	Cotton	150	25	April	May 10-20	-	June -Aug	Oct7-15
‘’	Sesame	120	20	April-may	June1-15	-	July-Aug	Oct 1-10
‘’	Sorghum	150	10	Late March	April 15-30	-	June-Aug	Sept 12-25
‘’	Groundnut	140	10	March -Apr	May 15-30	-	April -Aug	Oct 2-10
Perennial	Papaya	300	5	April –may	June 16-25	Oct 1-15	As required	After10-12ms
‘’	Banana	300	5	April-june	July 1-15	Dec 15-30	As required	After10-12 ms
‘’	Coffee	3 years	15	April –may	June 20-30	Jan 1-15	As required	After 3 yrs
‘’	Orange	3-5years	10	May-Aug	Sept 1-15	Dec 1-15	As required	After 3-5yrs
Dry season	Green bean	90	10	Late oct-early Nov	-	Nov 16-25	Dec -Jan	Feb-14-25
‘’	Tomato	125	20	Oct	-	Nov 5-16	Dec-Feb	March 10-20
‘’	Pepper	130	10	Late sept-early oct	-	Oct 26-nov15	Nov-Jan	March 5-15
‘’	Onion	120	25	Late oct-early Nov	-	Nov 20-30	Dec -Feb	March 20-30

Appendix 9. Growth stages of proposed crops

Crop Type	Optimum root depth (m)	Growth stage				
		1st	2nd	3rd	4th	Total
Sorghum	1.2	20	35	55	40	150
Cotton	1.2	15	30	65	40	150
Sesame	1.2	15	25	60	20	120
Ground nut	0.9	35	45	35	25	140
Coffee	1.8	60	90	120	95	365
Orange	1.8	60	90	120	95	365
Banana	0.9	50	80	160	70	360
Papaya	1	50	80	160	70	360
Tomato	1.2	15	25	65	20	125
Onion	0.6	15	25	60	20	120
Pepper	1	30	35	40	25	130
Green bean	0.9	20	30	30	10	90

Appendix 10. Coefficient reflecting the growth stage of the crop (MOWR,2008)

Crop	**Kc**				Growth	stage				
Type	**1st**	**2nd**	**3rd**	**4th**	1st	2nd	3rd	4th	Total	in months
Sorghum	0.3	-	1.1	0.75	20	35	55	40	150	5
Cotton	0.45	-	1.1	0.8	15	30	65	40	150	5
Sesame	0.4	-	1.1	0.7	15	25	60	20	120	4
Green beans	0.35	-	1	0.85	35	45	35	25	140	4,20days
Groundnut	0.4	-	1	0.8	60	90	120	95	365	12
Banana	0.45	-	1	0.85	60	90	120	95	365	12
Papaya	0.65	-	1	0.8	50	80	160	70	360	12
Tomato	0.45	-	1.05	0.8	15	25	65	20	125	4,5days
Onion	0.45	-	1	0.85	15	25	60	20	120	4,5days
Pepper	0.4	-	1.05	0.8	30	35	40	25	130	4,10days
Coffee	1	-	1.1	1	60	90	120	95	365	12
Orange	0.65	-	1	0.8	60	90	120	95	365	12

Appendix 11. The cropping pattern and area coverage of crops (Cited from MWOR, 2008)

Crops	Wet season Area (%)	Dry season Area (%)	Area (ha)
Sorghum	10	-	1,800
Cotton	25	-	4,500
Sesame	20	-	3,600
Papaya	5	5	900
Banana	5	5	900
Tomato	-	20	3,600
Onion	-	25	4,500
Green beans	-	10	1,800
Pepper	-	10	1,800
Ground nut	10	-	1,800
Coffee	15	15	2,700
Orange	10	10	1,800
Total	**100**	**100**	**-**

Appendix 12 Growth stage and crop coefficient of the selected crops

Crop Type	**Kc**				Growth stage				
	1st	**2nd**	**3rd**	**4th**	1st	2nd	3rd	4th	Total
Sorghum	0.3		1.1	0.75	20	35	55	40	150
Cotton	0.45	-	1.1	0.8	15	30	65	40	150
Sesame	0.4	-	1.1	0.7	15	25	60	20	120
Green beans	0.35	-	1	0.85	35	45	35	25	140
Groundnut	0.4	-	1	0.8	60	90	120	95	365
Banana	0.45	-	1	0.85	60	90	120	95	365
Papaya	0.65	-	1	0.8	50	80	160	70	360
Tomato	0.45	-	1.05	0.8	50	80	160	70	360
Onion	0.45	-	1	0.85	15	25	65	20	125
Pepper	0.4	-	1.05	0.8	15	25	60	20	120
Coffee	1	-	1.1	1	30	35	40	25	130
Orange	0.65	-	1	0.8	20	30	30	10	90

Appendix 13. Metrological data used for estimating CWR and Irr. Requirement.

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
AMINT	11	13	14	15	16	17	17	16	15	14	13	12
AMAXT	27	28	29	30	31	33	32	30	30	30	28	27
MAT	19	21	22	23	24	25	25	23	23	22	21	20
MSD,h	7.86	7.68	8.05	8.14	8.38	6.62	5.68	6.19	6.67	8.58	9.13	8.28
WS,Km/s	1890	2060	2110	1900	1680	1940	1920	1600	1200	1300	1460	1610
MMR,mm	33.4	33.3	63.3	76.8	58.9	26.2	125	187.8	66.6	42	24	17.04
RH %	8.7	8.7	8.4	8.1	7.4	6.6	8.7	9.3	9.2	8.5	8	8.5

MSD= monthly sunshine duration, WS= wind speed, RH= relative humidity

Appendix 14 Irrigation requirement of crops

14.1 Irrigation Requirement (irr.Req.) of cotton

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
May	1	Init	0.45	2.65	2.7	2	2.7
May	2	Init	0.45	2.62	26.2	18.4	7.8
May	3	Deve	0.51	3	33	15.1	17.9
Jun	1	Deve	0.72	4.37	43.7	8.3	35.4
Jun	2	Deve	0.94	5.79	57.9	3.5	54.4
Jun	3	Mid	1.1	6.69	66.9	13.5	53.5
Jul	1	Mid	1.1	6.67	66.7	26.4	40.3
Jul	2	Mid	1.1	6.6	66	35.4	30.6
Jul	3	Mid	1.1	6.4	70.4	38.2	32.2
Aug	1	Mid	1.1	6.2	62	43.6	18.4
Aug	2	Mid	1.1	6	60	48.7	11.3
Aug	3	Late	1.1	5.74	63.1	39.1	24
Sep	1	Late	1.03	5.17	51.7	26.2	25.5
Sep	2	Late	0.95	4.58	45.8	17.4	28.4
Sep	3	Late	0.87	4.23	42.3	16	26.3
Oct	1	Late	0.81	3.95	23.7	9.1	16.1
				Total	782.1	360.8	424.9

14.2. Irrigation Requirement of onion

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Nov	2	Init	0.45	2.1	2.1	0.7	2.1
Nov	3	Init	0.45	2.08	20.8	6.7	14.1
Dec	1	Deve	0.5	2.27	22.7	5.6	17.2
Dec	2	Deve	0.7	3.19	31.9	4.5	27.4
Dec	3	Mid	0.93	4.32	47.6	6.5	41
Jan	1	Mid	1	4.78	47.8	9.3	38.5
Jan	2	Mid	1	4.91	49.1	11.2	37.8
Jan	3	Mid	1	5.1	56.1	11	45.1
Feb	1	Mid	1	5.3	53	9.8	43.3
Feb	2	Mid	1	5.5	55	9.4	45.6
Feb	3	Late	1	5.67	45.4	12.6	32.8
Mar	1	Late	0.95	5.57	55.7	16.6	39.1
Mar	2	Late	0.88	5.31	47.8	17.7	28.1
				total	534.9	121.5	412.2

14.3. Irr.Req. of Pepper

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Oct	3	Init	0.4	1.93	11.6	6.1	6
Nov	1	Init	0.4	1.9	19	9.2	9.8
Nov	2	Init	0.4	1.87	18.7	7.3	11.4
Nov	3	Deve	0.44	2.03	20.3	6.7	13.6
Dec	1	Deve	0.61	2.81	28.1	5.6	22.5
Dec	2	Deve	0.8	3.62	36.2	4.5	31.7
Dec	3	Mid	0.99	4.61	50.7	6.5	44.2
Jan	1	Mid	1.05	5.02	50.2	9.3	40.9
Jan	2	Mid	1.05	5.15	51.5	11.2	40.3
Jan	3	Mid	1.05	5.36	59	11	48
Feb	1	Late	1.04	5.54	55.4	9.8	45.6
Feb	2	Late	0.97	5.31	53.1	9.4	43.7
Feb	3	Late	0.88	4.97	39.7	12.6	27.2
Mar	1	Late	0.81	4.77	19.1	6.6	10.8
				total	512.5	115.8	395.6

14.4. Irr.Req. Of Sesame

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Jun	1	Init	0.4	2.42	24.2	8.3	15.9
Jun	2	Deve	0.44	2.72	27.2	3.5	23.7
Jun	3	Deve	0.69	4.23	42.3	13.5	28.8
Jul	1	Deve	0.97	5.87	58.7	26.4	32.4
Jul	2	Mid	1.1	6.57	65.7	35.4	30.3
Jul	3	Mid	1.1	6.37	70.1	38.2	31.9
Aug	1	Mid	1.1	6.17	61.7	43.6	18.1
Aug	2	Mid	1.1	5.97	59.7	48.7	11
Aug	3	Mid	1.1	5.75	63.2	39.1	24.1
Sep	1	Late	1.09	5.49	54.9	26.2	28.7
Sep	2	Late	0.95	4.55	45.5	17.4	28.1
Sep	3	Late	0.76	3.69	29.5	12.8	13.5
				total	602.7	313	286.5

14.5. Irr.Req. Of Green beans

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Nov	2	Init	0.35	1.64	8.2	3.6	4.5
Nov	3	Init	0.35	1.62	16.2	6.7	9.5
Dec	1	Deve	0.38	1.76	17.6	5.6	12
Dec	2	Deve	0.58	2.65	26.5	4.5	22
Dec	3	Deve	0.82	3.81	41.9	6.5	35.4
Jan	1	Mid	1.01	4.81	48.1	9.3	38.8
Jan	2	Mid	1.02	5	50	11.2	38.8
Jan	3	Mid	1.02	5.2	57.2	11	46.2
Feb	1	Late	0.98	5.18	51.8	9.8	42
Feb	2	Late	0.88	4.85	14.6	2.8	9.9
				Total	332	71.1	259.1

14.6. Irr.Req. of Groundnut

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
May	2	Init	0.4	2.33	14	11.1	4.8
May	3	Init	0.4	2.37	26.1	15.1	11
Jun	1	Init	0.4	2.42	24.2	8.3	15.9
Jun	2	Deve	0.4	2.48	24.8	3.5	21.3
Jun	3	Deve	0.5	3.04	30.4	13.5	16.9
Jul	1	Deve	0.63	3.8	38	26.4	11.7
Jul	2	Deve	0.76	4.55	45.5	35.4	10.1
Jul	3	Deve	0.9	5.22	57.4	38.2	19.2
Aug	1	Mid	0.99	5.56	55.6	43.6	12.1
Aug	2	Mid	0.99	5.39	53.9	48.7	5.2
Aug	3	Mid	0.99	5.19	57.1	39.1	18
Sep	1	Late	0.98	4.94	49.4	26.2	23.2
Sep	2	Late	0.92	4.41	44.1	17.4	26.6
Sep	3	Late	0.83	4.04	40.4	16	24.4
Oct	1	Late	0.79	3.84	3.8	1.5	3.8
				Total	564.7	343.8	224.3

14.7. Irr.Req. of Sorghum

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
May	2	Init	0.3	1.75	10.5	11.1	1.3
May	3	Init	0.3	1.78	19.6	15.1	4.5
Jun	1	Deve	0.36	2.2	22	8.3	13.7
Jun	2	Deve	0.59	3.6	36	3.5	32.5
Jun	3	Deve	0.82	4.96	49.6	13.5	36.2
Jul	1	Mid	1.04	6.26	62.6	26.4	36.2
Jul	2	Mid	1.1	6.58	65.8	35.4	30.4
Jul	3	Mid	1.1	6.38	70.2	38.2	32
Aug	1	Mid	1.1	6.18	61.8	43.6	18.2
Aug	2	Mid	1.1	5.98	59.8	48.7	11.1
Aug	3	Mid	1.1	5.75	63.3	39.1	24.2
Sep	1	Late	1.06	5.32	53.2	26.2	27
Sep	2	Late	0.97	4.67	46.7	17.4	29.3
Sep	3	Late	0.88	4.27	42.7	16	26.7
Oct	1	Late	0.79	3.85	38.5	15.2	23.3
Oct	2	Late	0.74	3.63	3.6	1.3	3.6
				Total	706	358.8	350.4

14.8. Irr.Req. Of Tomato

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Nov	1	Init	0.45	2.14	12.8	5.5	8.2
Nov	2	Deve	0.45	2.11	21.1	7.3	13.8
Nov	3	Deve	0.61	2.82	28.2	6.7	21.5
Dec	1	Deve	0.85	3.92	39.2	5.6	33.6
Dec	2	Mid	1.05	4.75	47.5	4.5	43
Dec	3	Mid	1.06	4.95	54.5	6.5	48
Jan	1	Mid	1.06	5.08	50.8	9.3	41.5
Jan	2	Mid	1.06	5.22	52.2	11.2	40.9
Jan	3	Mid	1.06	5.43	59.7	11	48.7
Feb	1	Mid	1.06	5.64	56.4	9.8	46.6
Feb	2	Late	1.06	5.81	58.1	9.4	48.7
Feb	3	Late	0.97	5.51	44.1	12.6	31.5
Mar	1	Late	0.86	5.06	45.6	14.9	29
				Total	570.1	114.3	455.1

14.9 Irr.Req. of coffee

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Jun	2	Init	1.02	6.27	6.3	0.4	52.9
Jun	3	Init	1	6.09	60.9	13.5	47.5
Jul	1	Init	1	6.03	60.3	26.4	33.9
Jul	2	Init	1	5.97	59.7	35.4	24.4
Jul	3	Init	1	5.79	63.7	38.2	25.5
Aug	1	Init	1	5.61	56.1	43.6	12.6
Aug	2	Deve	1	5.43	54.3	48.7	5.7
Aug	3	Deve	1.01	5.28	58.1	39.1	19
Sep	1	Deve	1.02	5.14	51.4	26.2	25.2
Sep	2	Deve	1.04	4.99	49.9	17.4	32.5
Sep	3	Deve	1.05	5.08	50.8	16	34.9
Oct	1	Deve	1.06	5.18	51.8	15.2	36.6
Oct	2	Deve	1.08	5.27	52.7	12.9	39.8
Oct	3	Deve	1.09	5.26	57.8	11.2	46.7
Nov	1	Deve	1.1	5.24	52.4	9.2	43.2
Nov	2	Mid	1.12	5.21	52.1	7.3	44.9
Nov	3	Mid	1.12	5.17	51.7	6.7	45
Dec	1	Mid	1.12	5.12	51.2	5.6	45.6
Dec	2	Mid	1.12	5.07	50.7	4.5	46.2
Dec	3	Mid	1.12	5.21	57.3	6.5	50.8
Jan	1	Mid	1.12	5.35	53.5	9.3	44.1
Jan	2	Mid	1.12	5.48	54.8	11.2	43.6
Jan	3	Mid	1.12	5.71	62.8	11	51.8
Feb	1	Mid	1.12	5.93	59.3	9.8	49.5
Feb	2	Mid	1.12	6.15	61.5	9.4	52.1
Feb	3	Mid	1.12	6.35	50.8	12.6	38.2
Mar	1	Mid	1.12	6.54	65.4	16.6	48.9
Mar	2	Late	1.12	6.73	67.3	19.6	47.7
Mar	3	Late	1.11	6.67	73.4	20.6	52.8
Apr	1	Late	1.1	6.6	66	22.1	44
Apr	2	Late	1.08	6.53	65.3	23.6	41.7
Apr	3	Late	1.07	6.4	64	21.7	42.3
May	1	Late	1.06	6.26	62.6	19.8	42.9
May	2	Late	1.05	6.13	61.3	18.4	42.9
May	3	Late	1.04	6.18	68	15.1	52.9
Jun	1	Late	1.03	6.22	62.2	8.3	54
Jun	2	Late	1.02	6.27	56.4	3.2	52.9
				Total	2104.2	635.9	1515

Appendix 15 Estimated amount of water monthly required from the groundwater system
15.1 Raya valley groundwater system.

	Raya Valley	Monthly irrigation requirement of crops of the Raya valley, MCM											
Crop type	Area,Km	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Cotton	45					1.28	6.45	4.64	2.42	3.61	0.72		
Onion	45	5.46	5.48	3.02								0.73	3.85
Pepper	18	2.33	2.1	0.19							0.11	0.63	1.77
Sesame	36						2.46	3.41	1.92	2.53			
Green bean	18	2.23	0.93									0.25	1.25
Groundnut	18					0.28	0.97	0.74	0.64	1.34	0.07		
Sorghum	18					0.104	1.48	1.77	0.96	1.49	0.48		
Tomato	36	4.72	4.56	1.04								1.57	4.49
Coffee	27	4.17	3.69	4.03	3.46	3.74	2.71	2.26	1	2.5	3.32	3.59	3.85

15.2. Kobo valley groundwater system

	Monthly irrigation requirement of crops of the Kobo Valley, MCM												
Crop type	Area,Km	Jan	Feb	Mar	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Dec
Onion	1.23	0.15	0.15								0.02	0.11	0.11
Pepper	0.51	0.07	0.06	0.0055						0.0031	0.02	0.05	0.05
Sesame	1.01					0.07	0.1	0.05	0.07				
Green bean	0.51	0.063	0.026								0.007	0.035	0.035
Groundnut	0.51				0.0081	0.028	0.02	0.018	0.038	0.0019			
Sorghum	0.51				0.003	0.042	0.05	0.027	0.042	0.0136			
Tomato	1.01	0.132	0.128	0.029							0.044	0.126	0.126

Appendix 16 Description of selected sustainability indicators

S,N	Indicator	Characteristics and importance
1	Renewablegroundwater resources/Inhabitants	Estimate the total amount of ground water for many uses. Show how much groundwater is theoretically available for each inhabitant per year. This is driving force indicator of great significance to the planners, policy and decision makers and social and economic relevance.
2	Total GW abstraction X100% / GW recharge	Indicate excessive abstraction of GW without the understanding of recharge rates can cause problems, particularly depletion of the resource Three scenarios : 1. Groundwater abstraction less than90% of recharge implies sustainable groundwater use. 2. Groundwater abstraction= recharge, but may not show sustainability. 3. Groundwater abstraction more than 100% of recharge implies groundwater use needs management action.
3	Total abstraction GW X100% / Exploitable GW resources	Three scenarios are proposed: 1. Groundwater abstraction less the 90% of exploitable amount implies underdeveloped groundwater. 2. Groundwater abstraction= exploitable amount implies groundwater development is sustainable. 3. Groundwater abstraction more than 100% of exploitable amount implies over exploited groundwater resource and resulting stress.
4	Groundwater vulnerability = total area of vulnerability x100 / Total area under study	GW vulnerability is an intrinsic property of a groundwater system that depends on the ability of that system to cope with human and natural impacts. Vulnerability variables: soil, thickness of unsaturated zone lithology and depth of water table, aquifer media and hydraulic conductivity. Four classes of vulnerability are proposed: High Uppermost water table aquifers overlain by permeable sandy soils and by permeable unsaturated zone (sand, gravel, sandstone, chalk, limestone) of limited thickness (less than 10 m); deeper aquifers interconnected to the uppermost vulnerable aquifers; aquifers linked to surface water bodies; karstic aquifers; aquifers recharge area; part of aquifers in coastal area affected by seawater intrusion. Moderate Deeper water table aquifers or semi confined aquifers overlain by less permeable soil (sandy and silty loam, loam, aggregated clay) and less permeable unsaturated zone of thickness between 10 and 30 m. Low Deep confined renewable aquifers overlain by low permeable soil (clay loam, non aggregated clay) and a thick, low permeability unsaturated zone (more than 30 m). Deep mostly non-renewable aquifers with groundwater which is not part of the hydrological cycle under current conditions and during recent geological periods. The unsaturated zone consists of impermeable or less permeable rocks and often reaches a thickness of hundreds or even thousands of meters.

Appendix17. Population size of study areas

Region /Zone /Wereda	Urban + Rural			Urban			Rural		
	Both Sexes	Male	Female	Both Sexes	Male	Female	Both Sexes	Male	Female
Merab Este-Wereda	120,075	61,603	58,472	2,192	1,100	1,092	117,883	60,503	57,380
North Wello-Zone									
Zone Total	1,503,283	754,354	748,929	155,659	76,060	79,599	1,347,624	678,294	669,330
Bugna-Wereda	75,468	37,869	37,599	-	-	-	75,468	37,869	37,599
Kobo-Wereda	221,894	111,571	110,323	33,135	16,311	16,824	188,759	95,260	93,499
Gidan-Wereda	160,115	79,148	80,967	7,713	3,690	4,023	152,402	75,458	76,944
Meket-Wereda	227,338	114,731	112,607	11,748	5,697	6,051	215,590	109,034	106,556
Wadla-Wereda	128,145	64,553	63,592	4,289	1,943	2,346	123,856	62,610	61,246
Delanta-Wereda	128,411	64,068	64,343	7,847	3,907	3,940	120,564	60,161	60,403
Gubalafto-Wereda	139,800	70,732	69,068	4,885	2,377	2,508	134,915	68,355	66,560
Habru-Wereda	192,701	96,856	95,845	21,598	10,591	11,007	171,103	86,265	84,838
Woldiya /Town/-Wereda	46,126	22,990	23,136	46,126	22,990	23,136	-	-	-
Lasta-Wereda	118,185	58,648	59,537	17,790	8,317	9,473	100,395	50,331	50,064
Dawunt-Wereda	65,100	33,188	31,912	528	237	291	64,572	32,951	31,621
Southern Tigray-Zone									
Zone Total	1,004,558	496,444	508,114	124,813	58,945	65,868	879,745	437,499	442,246
Seharti Samre-Wereda	124,499	61,954	62,545	9,185	4,290	4,895	115,314	57,664	57,650
Enderta-Wereda	114,277	57,472	56,805	-	-	-	114,277	57,472	56,805
Hintalo Wajirat-Wereda	152,219	75,262	76,957	11,928	5,627	6,301	140,291	69,635	70,656
Alaje-Wereda	107,954	52,840	55,114	7,565	3,668	3,897	100,389	49,172	51,217
Endamehoni-Wereda	84,726	42,048	42,678	2,985	1,278	1,707	81,741	40,770	40,971
Raya Azebo-Wereda	136,039	67,774	68,265	16,055	7,626	8,429	119,984	60,148	59,836
Alamata-Wereda	85,359	42,460	42,899	4,563	2,133	2,430	80,796	40,327	40,469
Ofla-Wereda	126,953	62,311	64,642	-	-	-	126,953	62,311	64,642
Maychew /Town/-Wereda	23,484	11,057	12,427	23,484	11,057	12,427	-	-	-
Korem /Town/-Wereda	15,850	7,135	8,715	15,850	7,135	8,715	-	-	-
Alamata /Town/-Wereda	33,198	16,131	17,067	33,198	16,131	17,067	-	-	-

Appendix18. Source of drinking water of weredas of the study areas

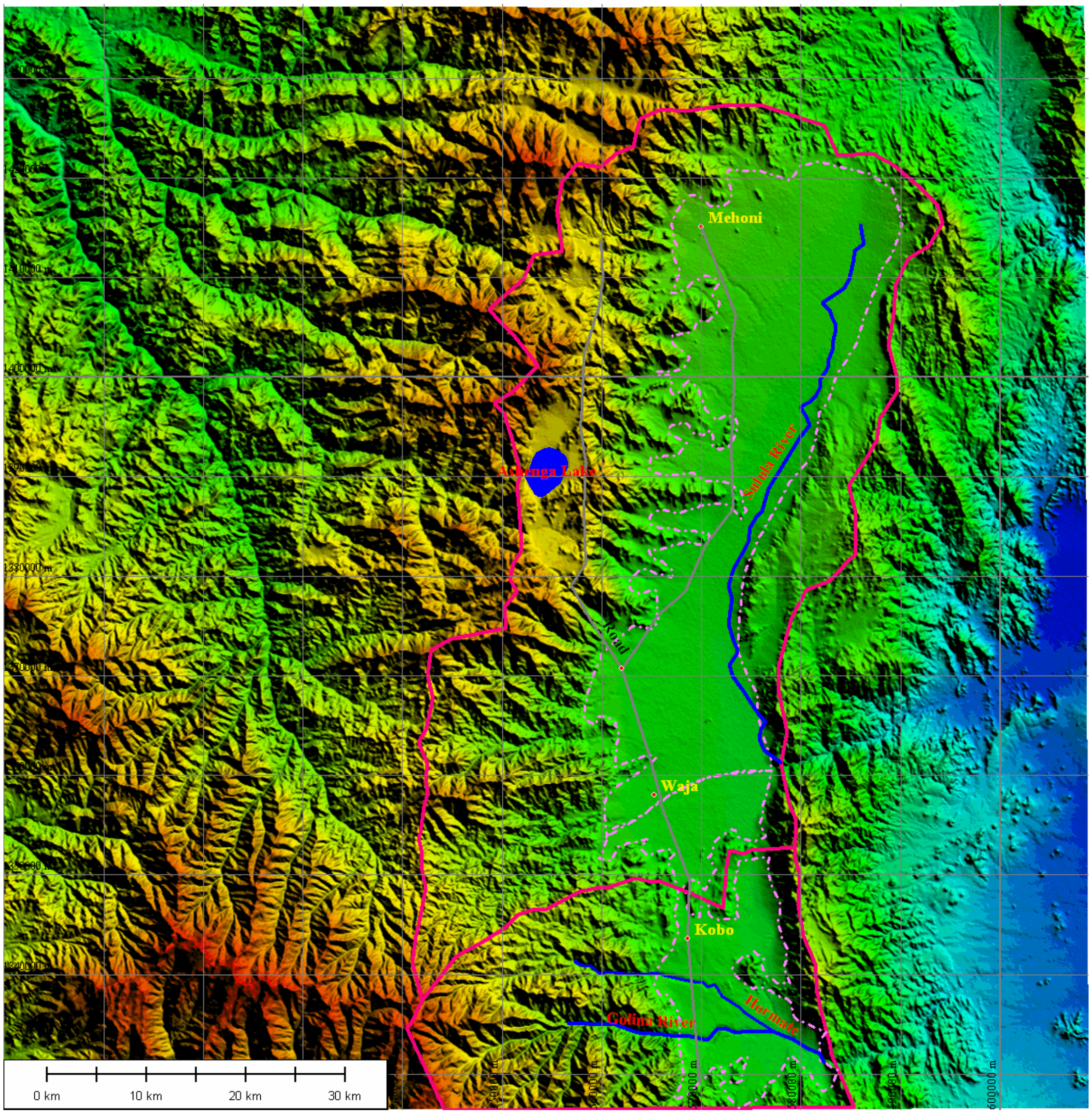
Geographical Area	All Housing Units	Source of Drinking Water: Tap Inside the House	Tap in Compound, Private	Tap in Compound, Shared	Tap Outside Compoud	Protected Well or Spring	Unprotected Well or Spring	River/ Lake/ Pond
KOBO-WEREDA	9,092	4,456	40	35	126	186	1,591	2,658
KOBO-TOWN	6,718	3,258	35	30	106	171	996	2,122
ROBIT-TOWN	1,607	739	-	5	20	15	434	394
GOBEYE-TOWN	767	459	5	-	-	-	161	142
ENDAMEHONI-WEREDA	882	5	66	66	635	40	40	30
MESWAET-TOWN	882	5	66	66	635	40	40	30
RAYA AZEBO-WEREDA	4,444	289	689	1,203	2,207	30	21	5
MEHONI-TOWN	3,814	252	615	1,028	1,884	25	5	5
CHERCHER-TOWN	630	37	74	175	323	5	16	-
ALAMATA-WEREDA	1,252	87	97	102	966	-	-	-
WAJA TEMUGA-TOWN	1,252	87	97	102	966	-	-	-
MAYCHEW/TOWN/-WEREDA	7,101	626	1,497	3,227	1,476	122	56	97
MAYCHEW-TOWN	7,101	626	1,497	3,227	1,476	122	56	97
KOREM/TOWN/-WEREDA	4,732	260	749	1,206	2,278	101	21	117
KOREM-TOWN	4,732	260	749	1,206	2,278	101	21	117
ALAMATA/TOWN/-WEREDA	8,848	339	1,736	3,338	3,405	15	15	-
ALAMATA-TOWN	8,848	339	1,736	3,338	3,405	15	15	-

Appendix 19 Factors affecting groundwater vulnerability (Groundwater indicators group, 2007)

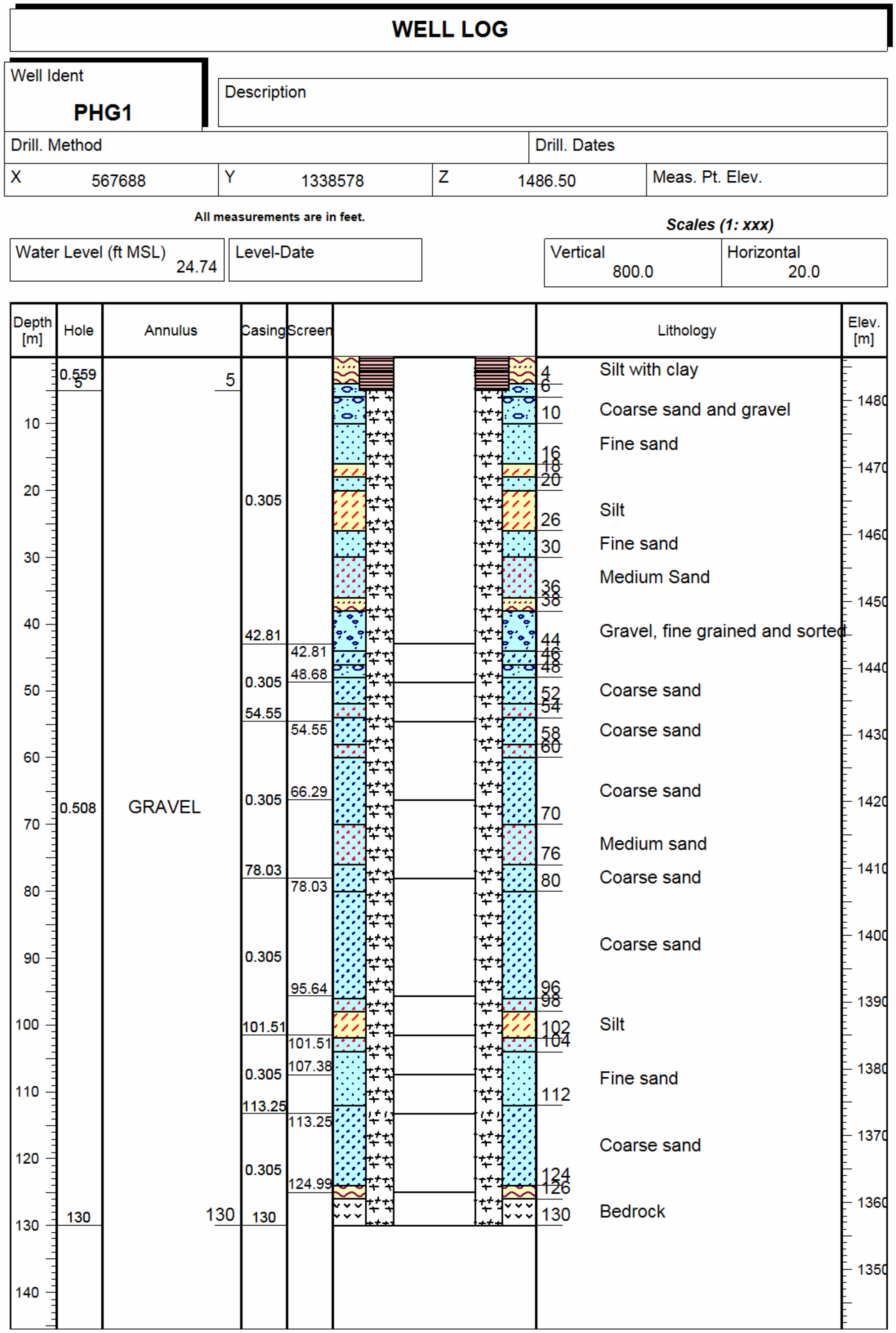
features	Weight
Soil media	2
Depth to water table	4
Unsaturated zone lithology	5
Aquifer media	3

Soil media	Rating
Thin or absent	5
Gravel	4
Sand	3
Loam	2
Clay	1
Depth to water table	Rating
0-2	5
2-5	4
5-10	3
10-20	2
20+	1
Unsaturated zone lithology	Rating
Coarse	5
Sand	4
Fine	3
Till	2
Silt and clay	1
Aquifer media	Rating
Coarse	5
Sand	4
Fine	3
Till	2
Silt and clay	1

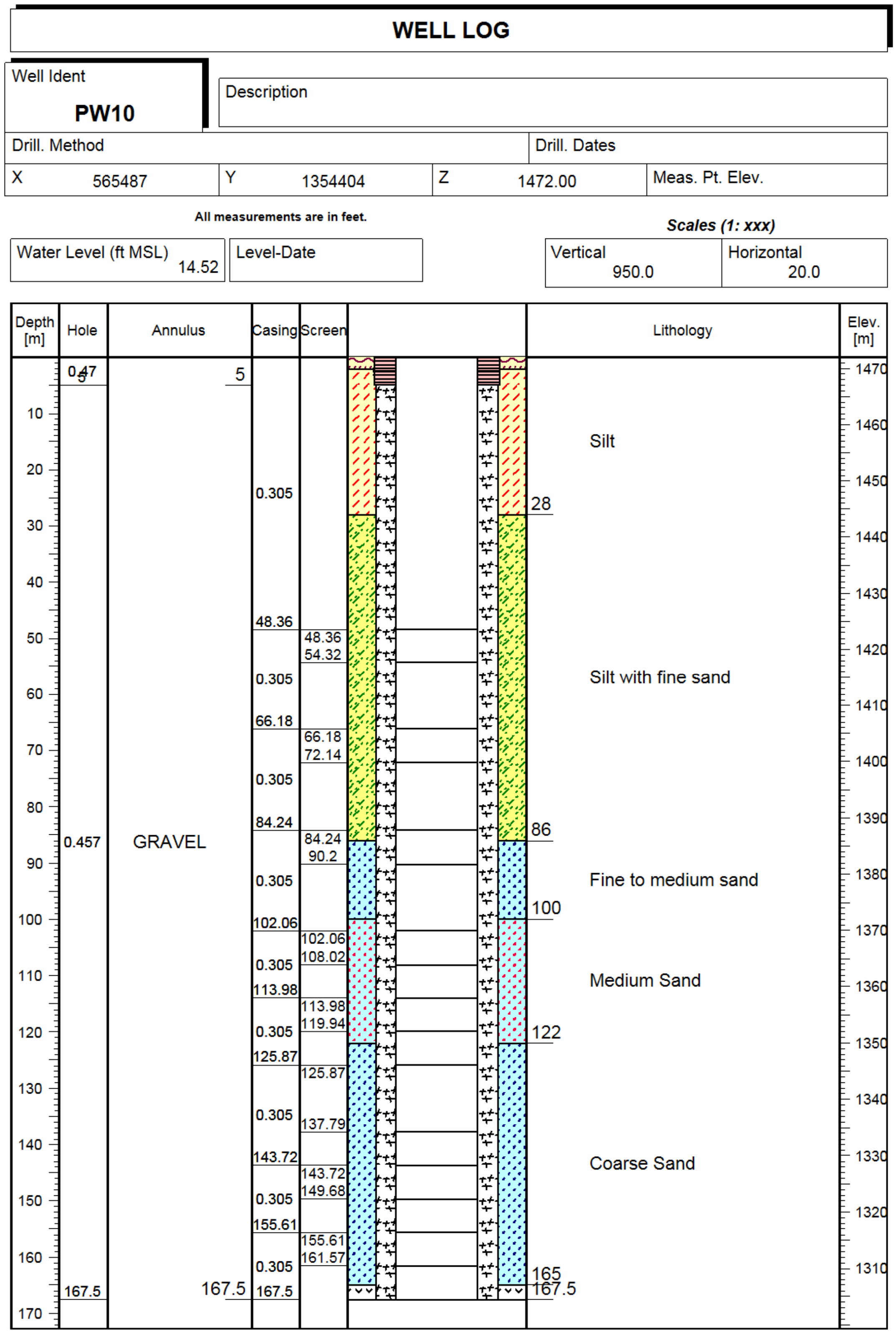
Appendix 20 Delineated aquifer and basin boundary of the study area



Appendix 21 a) Lithological logs of some of wells of Kobo Valley (MoWR and MCE.2008)



b)



WELL LOG
Well Ident
PW10
Description
Drill. Method
Drill. Dates
X 565487
Y 1354404
Z 1472.00
Meas. Pt. Elev.
All measurements are in feet.
Scales (1: xxx)
Water Level (ft MSL) 14.52
Level-Date
Vertical 950.0
Horizontal 20.0
Depth [m]
Hole
Annulus
Casing
Screen
Lithology
Elev. [m]
0.457
GRAVEL
Silt
28
Silt with fine sand
86
Fine to medium sand
100
Medium Sand
122
Coarse Sand
165
167.5